Constraining Electron Neutrino Background for Low Energy Neutrino Oscillation Experiments

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Outline

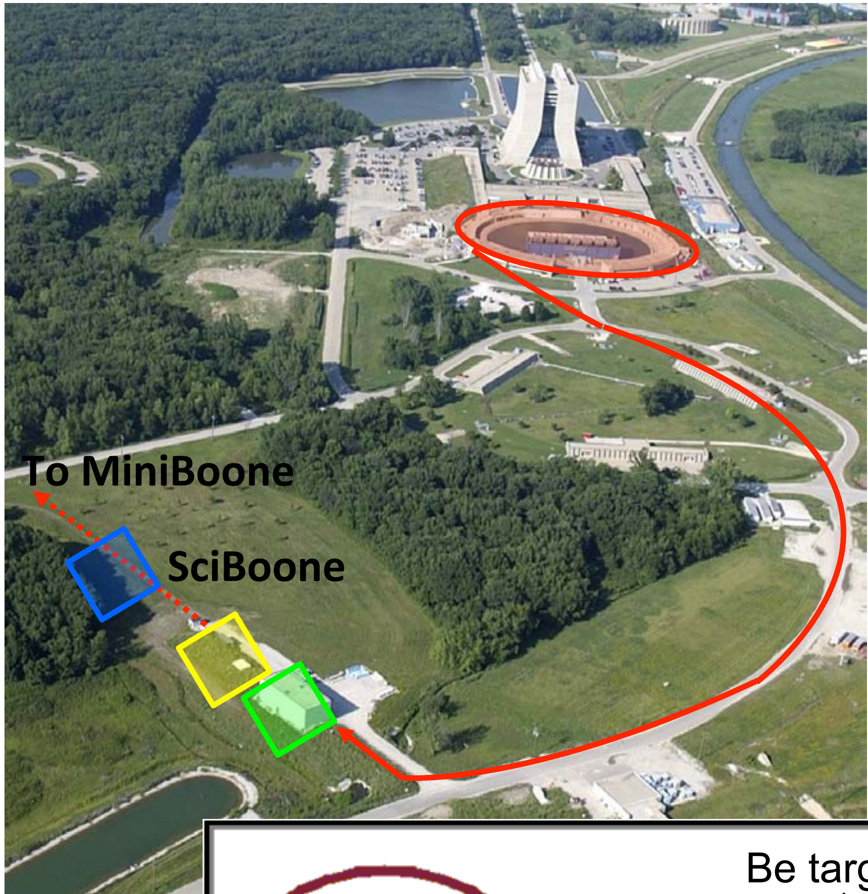
- Kaon Production by proton
  - Using SciBooNE high energy neutrino events
- ν_e Backgrounds to Oscillation experiments
  - Why it is important and hard to isolate Kaon background
- Predicting Kaon production:
  - Feynman Scaling model
  - Fit to available data
  - Include SciBooNE measurement
  - Constraining K^+ production will reduce MiniBooNE error

Kaon Production

K^+ production by protons at low energy is not well know and contribute to one of the main background to appearance neutrino oscillation experiments. Different measurements can be performed:

- Fixed target experiments (HARP, NA61)
- Neutrinos
  - Use the BNB – 8.9 GeV protons
  - Identify neutrinos from K^+ decay ($K^+ \rightarrow \mu + \nu_\mu$) using SciBooNE experiment data
  - Measure the $p + Be \rightarrow K^+ + X$ cross-section at the BNB energy

BNB and SciBooNE experiment



Booster Proton accelerator

- 8.9 GeV protons sent to target

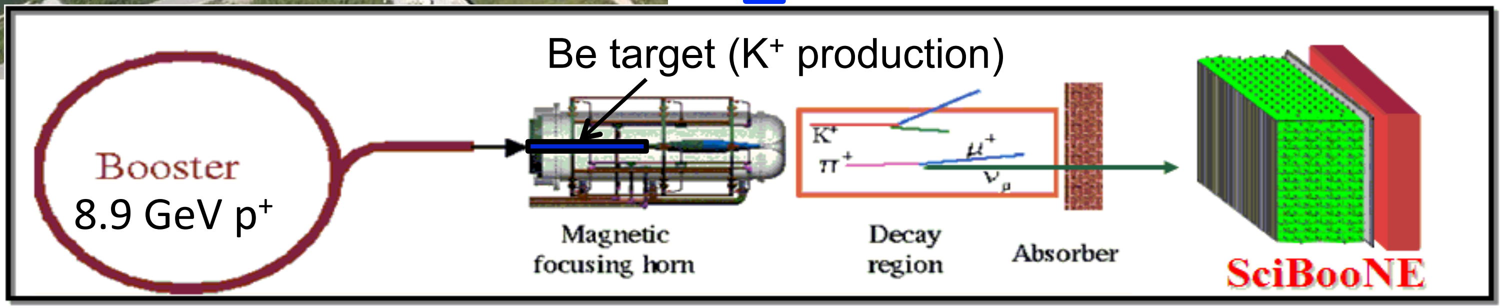
Target Hall

- 71cm long, 1cm diameter Be cylinder
- Resultant mesons focused with magnetic horn
- Reversible horn polarity

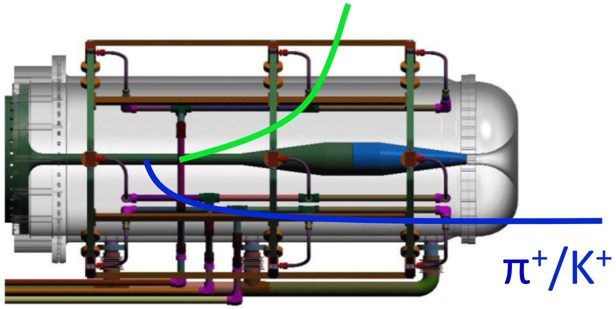
50m decay volume

- Mesons mostly decay to μ and ν_μ
- ν_e contamination from K^+ and μ^+

SciBooNE located 100m from target



Kaon Production @ BNB

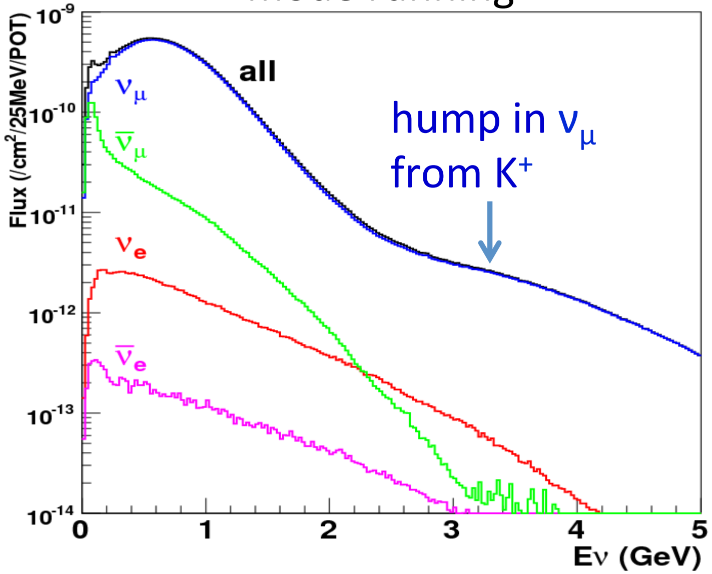


horn in neutrino mode running

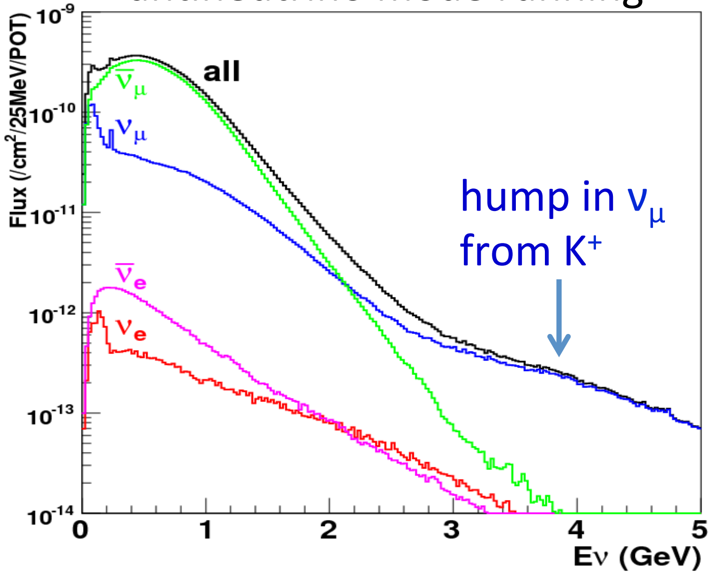
At the BNB:

$$p + Be \rightarrow (\pi^+ \ or \ \pi^- \ or \ K^+ \ or \ K^- or \ K_0^L) + X$$

ν flux at SciBooNE detector in neutrino mode running



ν flux at SciBooNE detector in antineutrino mode running



$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

ν_e 56%

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

$$K^+ \rightarrow \mu^+ + \nu_\mu$$

$$K^+ \rightarrow \pi^0 + \mu^+ + \nu_\mu$$

$$K^+ \rightarrow \pi^0 + e^+ + \nu_e$$

34%

$$K^- \rightarrow \mu^- + \bar{\nu}_\mu$$

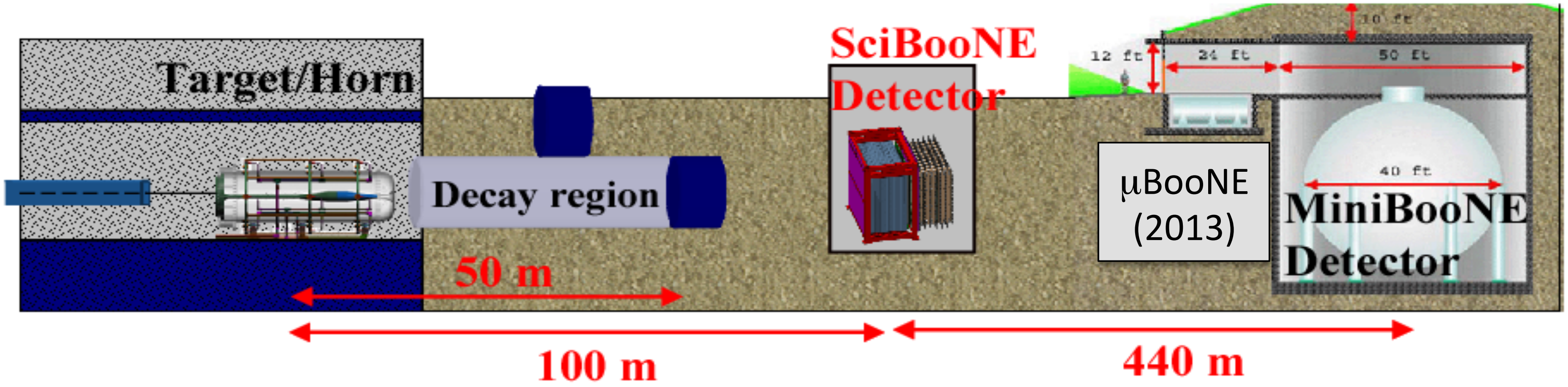
$$K^- \rightarrow \pi^0 + \mu^- + \bar{\nu}_\mu$$

$$K^- \rightarrow \pi^0 + e^- + \bar{\nu}_e$$

$$+K_0^L$$

ν_e 10%

SciBooNE Experiment



- Designed for precision neutrino-nucleus and antineutrino-nucleus cross-section measurements.

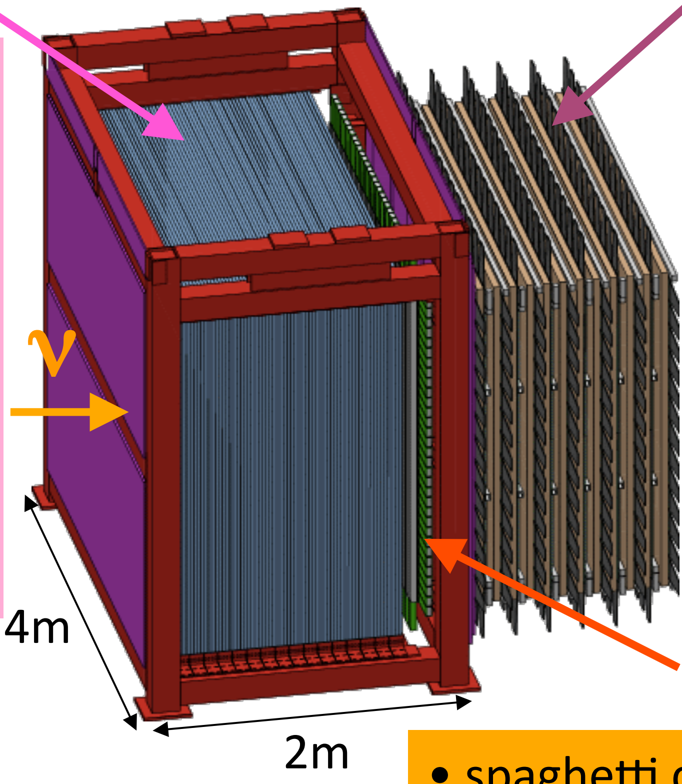
- Centered on the neutrino beam axis in front of the MiniBooNE detector.

SciBooNE Detector

SciBar

- scintillator tracking detector (CH)
- 14,336 scintillator bars (15 tons)
- Neutrino target
- detect all charged particles
- p/π separation using dE/dx

Used in K2K experiment



Muon Range Detector (MRD)

- 12 2”-thick iron + scintillator planes
- measure muon momentum with range up to 1.2 GeV/c

Built at Fermilab

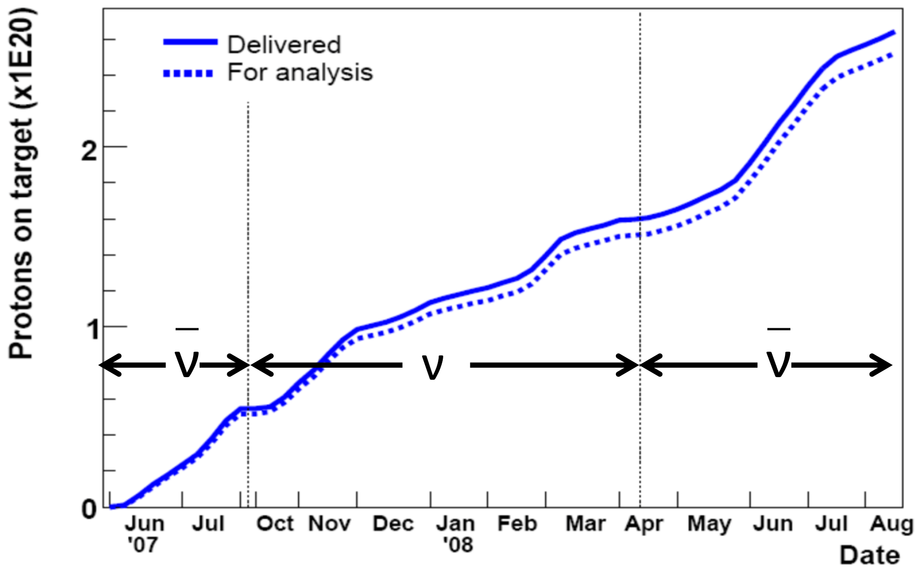
Electron Catcher (EC)

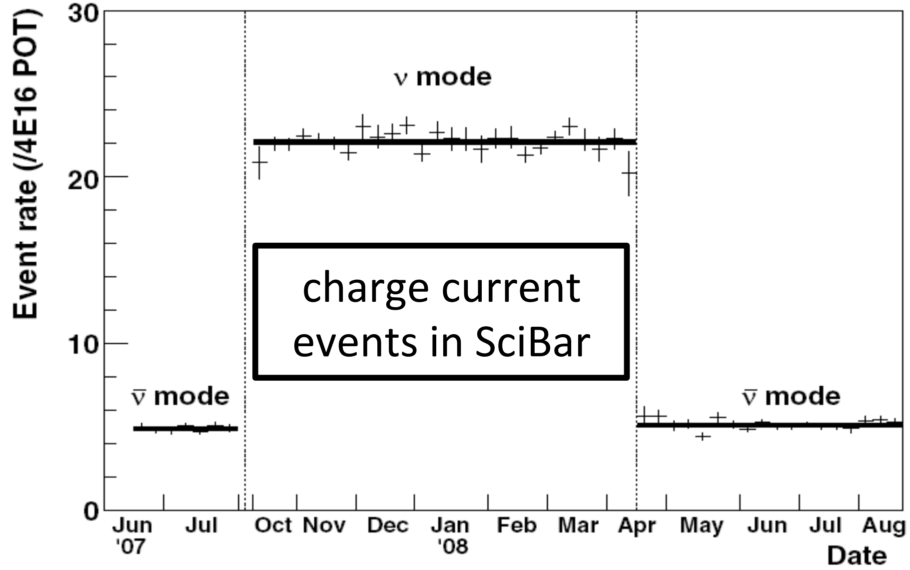
- spaghetti calorimeter
- 2 planes (11 X_0 Total)
- identify π^0 and e

Used in CHORUS, HARP and K2K

How do we measure K^+ production at proton target using neutrinos ?

Data Run





95.5% data collection efficiency for entire run

Run	Period	POT
Run 1 (Antineutrino)	Jun. 2007 - Aug. 2007	0.52×10^{20}
Run 2 (Neutrino)	Oct. 2007 - Apr. 2008	0.99×10^{20}
Run 3 (Antineutrino)	Apr. 2008 - Aug. 2008	1.01×10^{20}

A total of 2.52×10^{20} protons on target (POT) were collected. 0.99×10^{20} POT in neutrino mode and 1.53×10^{20} POT in antineutrino mode. The entire data set (both neutrino and antineutrino mode) is used in the analysis.

MC Simulation

- There are three distinct stages of MC simulation in SciBooNE:
  - Beam MC
  - Neutrino MC
  - Detector MC.

MC Simulation

- Beam MC: Custom code that models the interaction of protons on Be target, the production of mesons, the magnetic horn's focusing/defocusing of the mesons, and the meson's decay into neutrinos.
  - K^+ simulated using Feynman scaling parameterization and fitting data at higher proton momentum. Value of the K^+ double-differential cross section:

$$\frac{d^2\sigma}{dpd\Omega} = (6.303 \pm 2.017) mb / (GeV / c \times sr)$$

Output of the SciBooNE analysis will be measuring a ratio data/MC for the cross section

  - Error is 32% due not only to the Feynman Scaling model but also due to the uncertainty in the extrapolation from higher proton momentum data to the BNB and normalization of data sample

MC simulation cont'd

- $\pi^{\pm}$ simulated using Sanford-Wang parameterization and using very accurate data on $\pi^{\pm}$ production from the HARP experiment

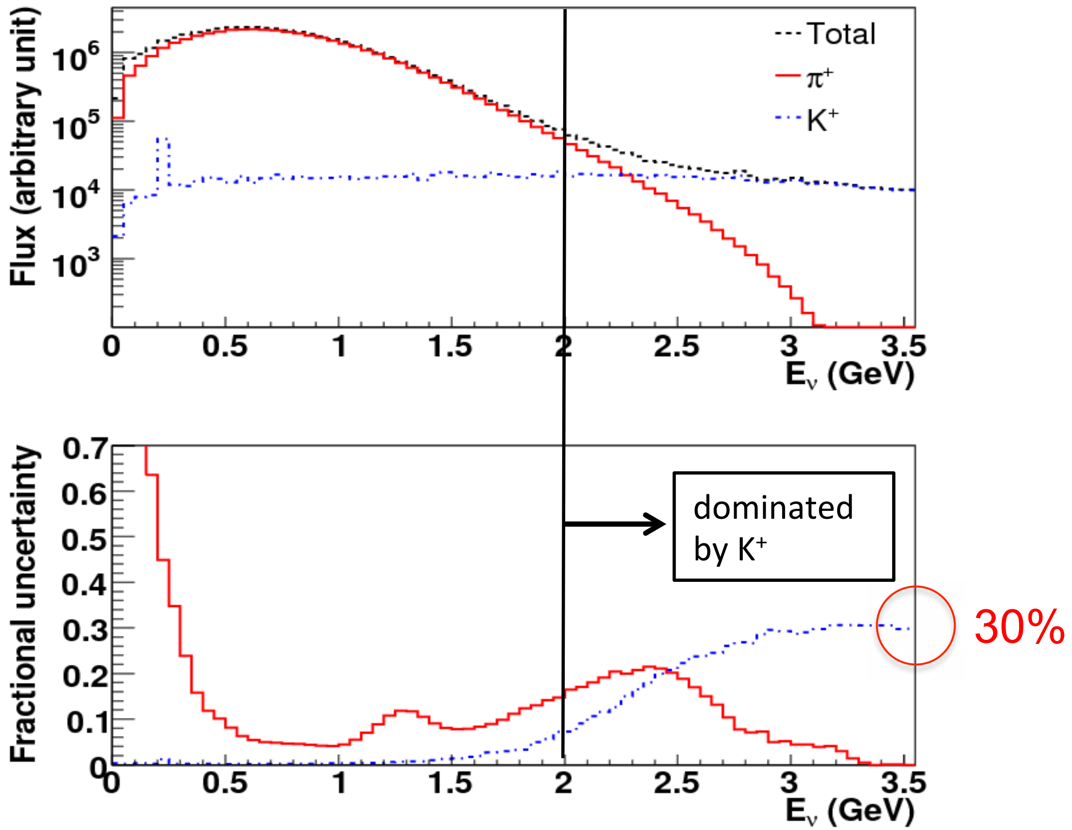
- Same beam MC simulation is used by:
  - SciBooNE
  - MiniBooNE
  - microBooNE (in construction)

MC Simulation

- Neutrino MC: Models the neutrino interaction on nuclei in the detector and the subsequent nuclear effects, returning final state charged particles that interact with the detector material.
  - two independent generators: **NUANCE** and **NEUT**

- Detector MC: GEANT4 models the interaction of final state charged particles with the detector material (scintillator, steel, etc.) simulating the electronic signals that are read in by the photomultiplier tubes. The MC at this stage mirrors the data, except the truth information is also passed.

Cut 1: Select ν of high energy



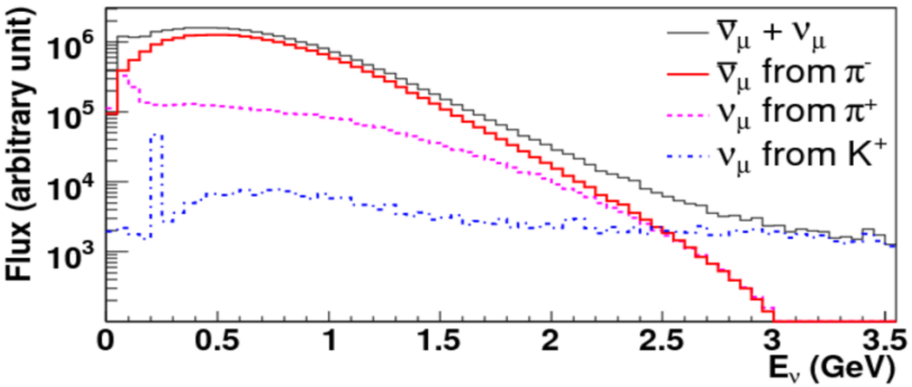
Parent contribution to ν_μ flux at SciBooNE detector in neutrino mode

The ν_μ flux at higher neutrino energies is dominated by the parent particle K^+ instead of parent particle π^+. The **difference in energy** will be one of the criteria to select a pure K^+ sample for analysis.

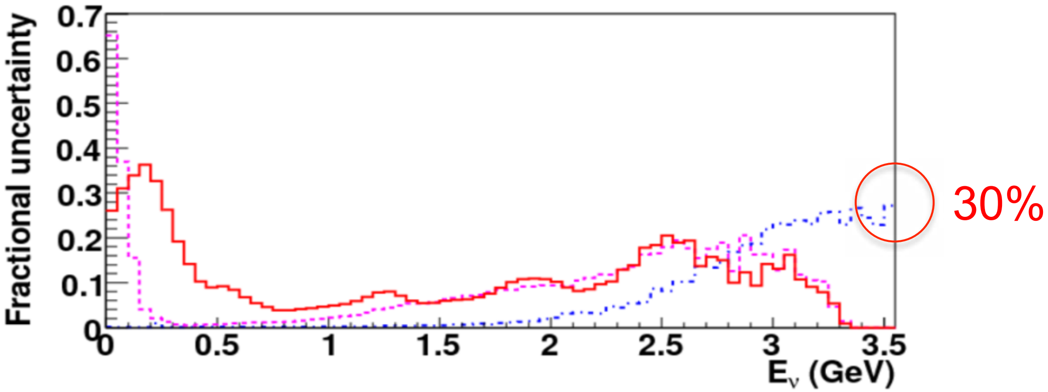
Fractional uncertainty of the ν flux prediction due to π^+ and K^+ production from the p-Be interaction in neutrino running mode.

Cut 1: Select ν of high energy in the $\bar{\nu}_\mu$ sample

Parent contribution to ν_μ and $\bar{\nu}_\mu$ flux at SciBooNE detector in antineutrino mode



Contribution to the neutrino Flux due to K^- and K_0^L is very small and is not shown in this plots.

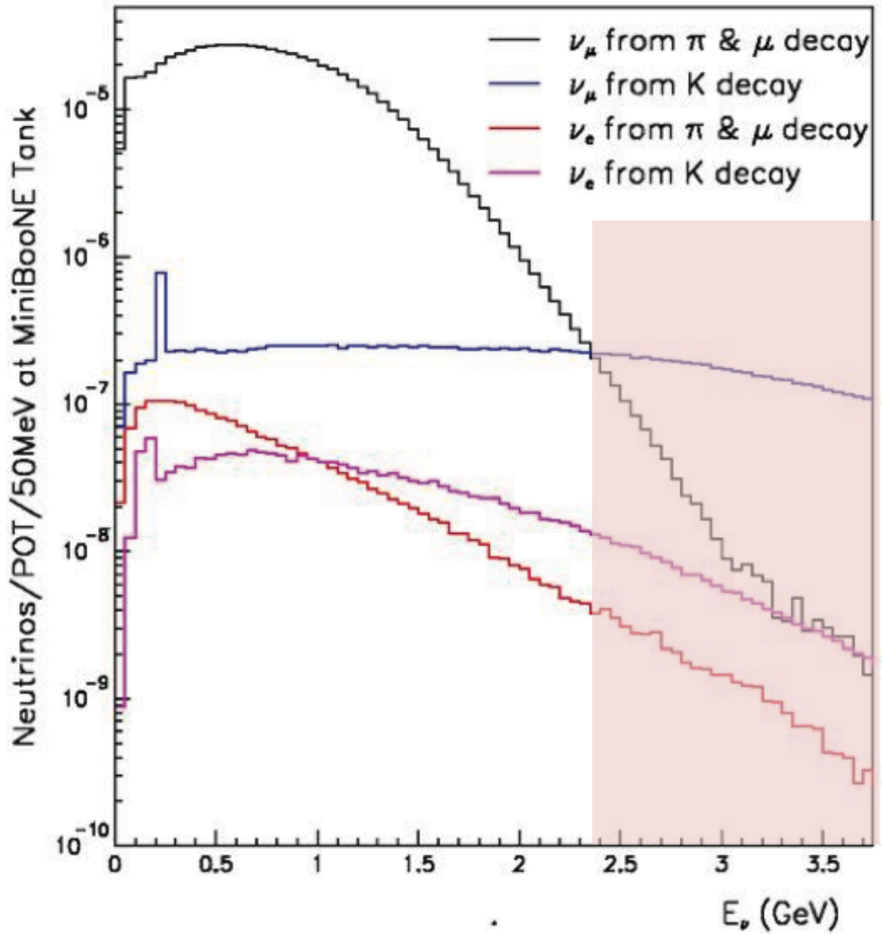


Fractional uncertainties of the ν_μ and $\bar{\nu}_\mu$ flux prediction only due to π^-, π^+ and K^+ production from the p-Be interaction in antineutrino running mode.

How to measure Kaon production using neutrinos

$$\nu_{\mu} + N \rightarrow \mu + X$$

High energy ν_{μ} (> 2 GeV) are mainly produced by K^{+}



How to measure Kaon production using neutrinos

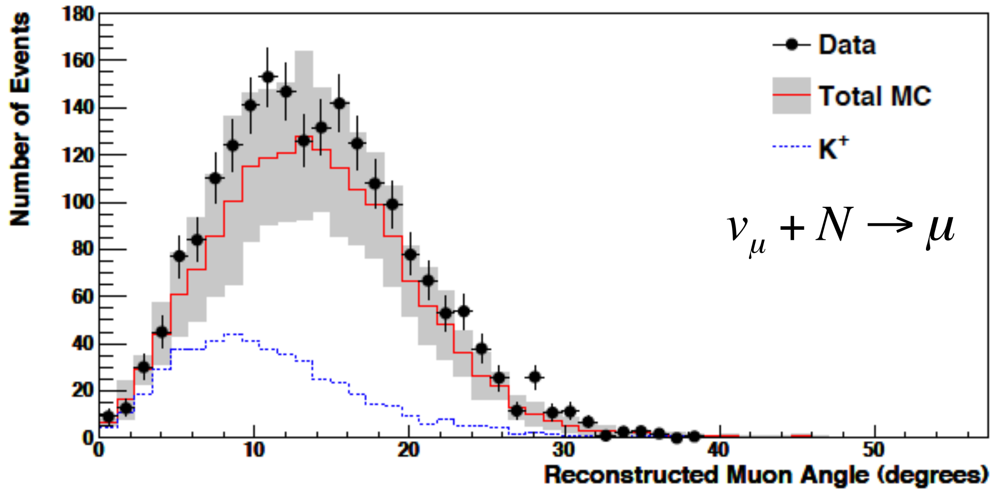
$$\nu_\mu + N \rightarrow \mu + X$$

High energy ν_μ (>2GeV) are mainly produced by K^+

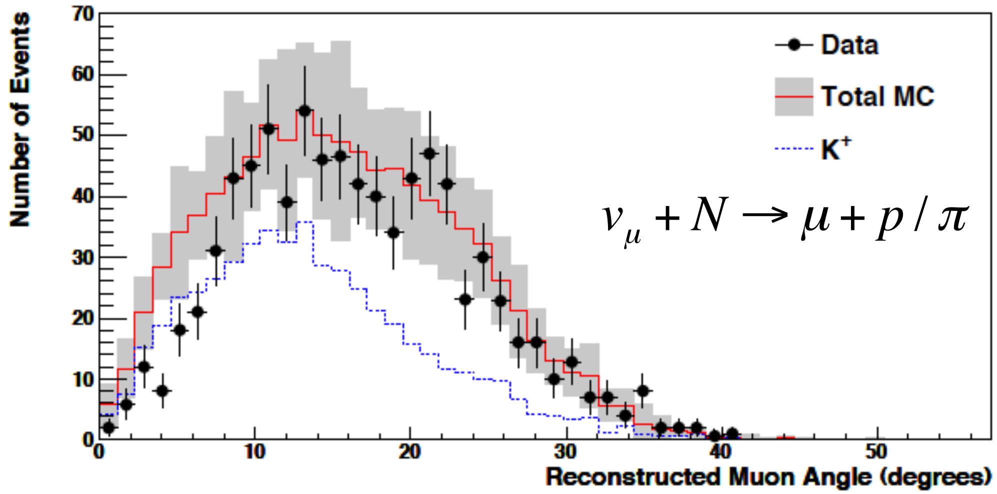
↓

High energy ν_μ produced high energy muon that will have small angle with respect to the neutrino beam direction

Angular distribution



(a) 1-Track Sample



(b) 2-Track Sample

How to measure Kaon production using neutrinos

$$\nu_\mu + N \rightarrow \mu + X$$

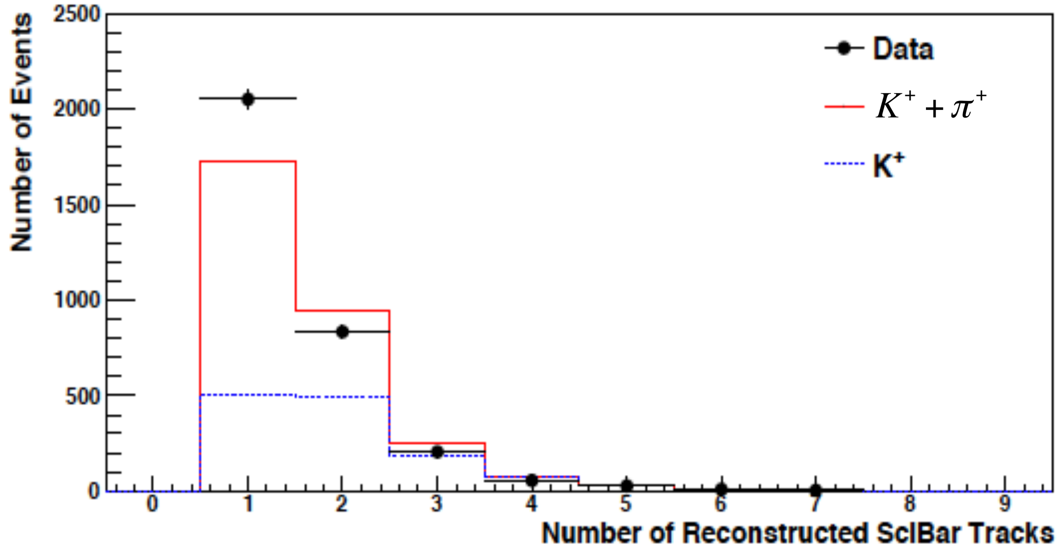
High energy ν_μ (>2GeV) are mainly produced by K^+

↓

High energy ν_μ produced high energy muon that will have smaller angle with respect to the neutrino beam direction
Angular distribution

↓

Neutrino have a lot of energy so the number of tracks produced in the neutrino interactions is high
High track multiplicity events



How to measure Kaon production using neutrinos

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↓

High energy ν_μ produced high energy muon that will have smaller angle with respect to the neutrino beam direction
Angular distribution

↓

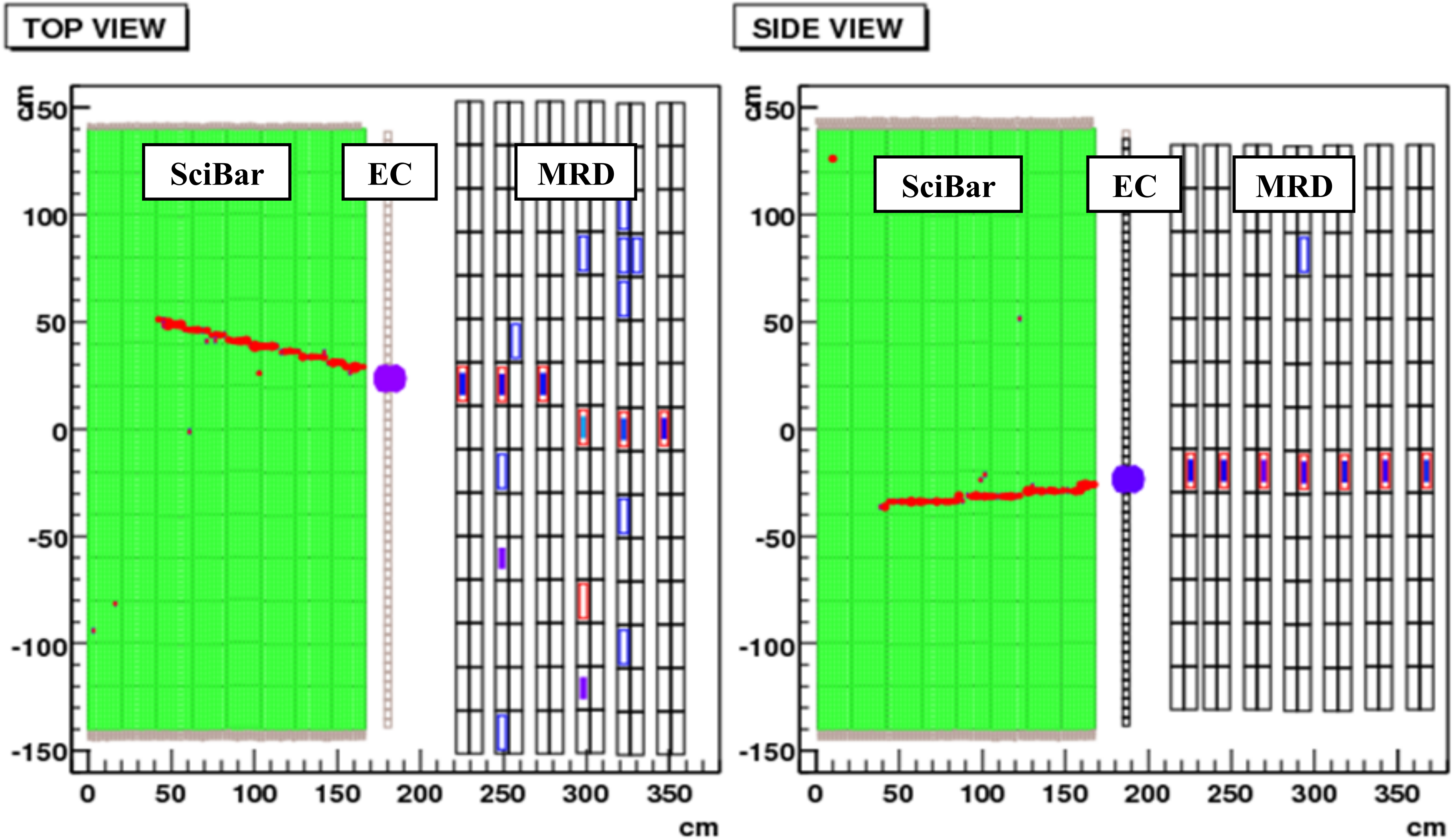
Neutrino have a lot of energy so the number of track produced in the interaction will be high
high track multiplicity events

→

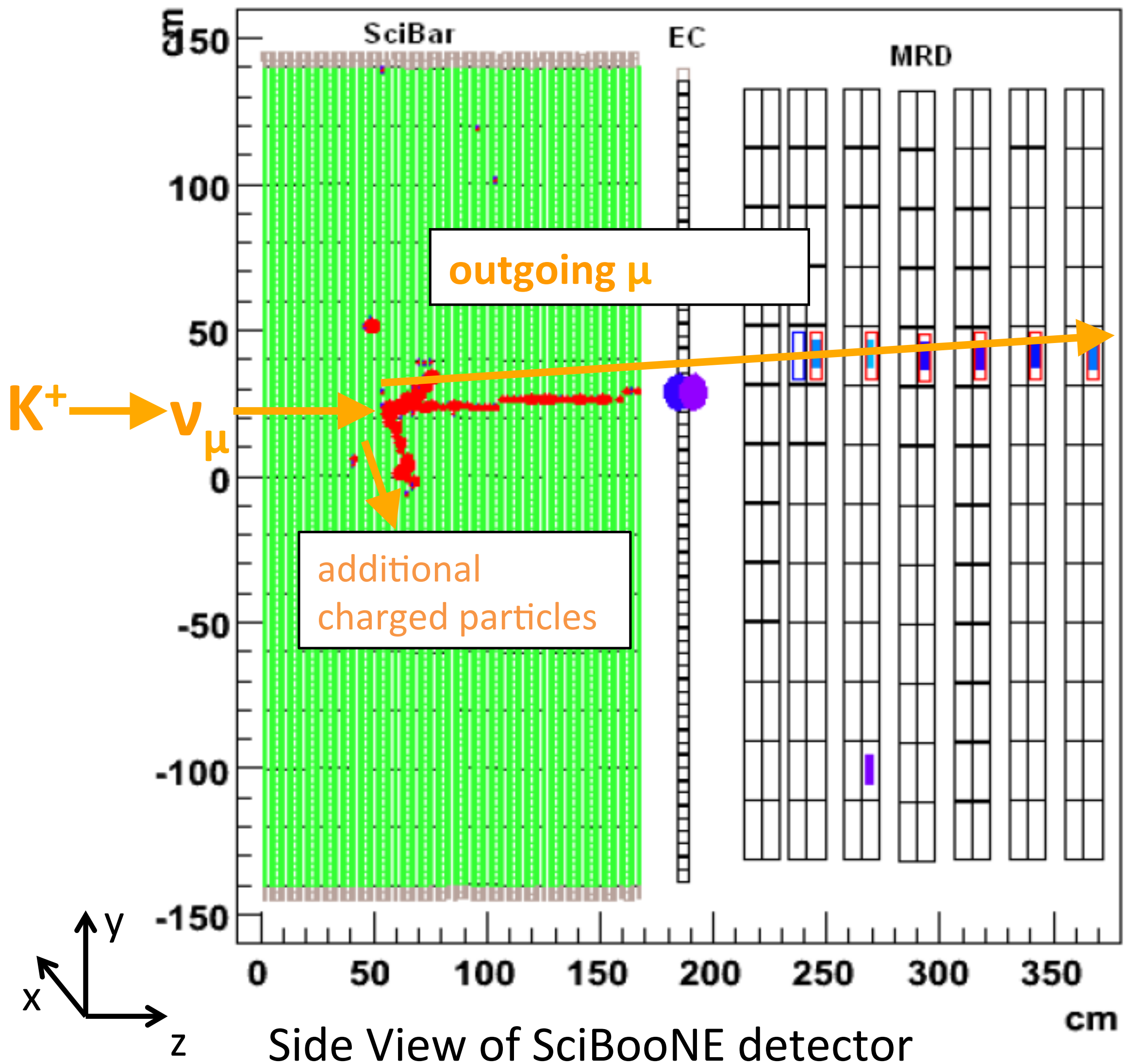
Analysis Outline

– Event selections
– Sample kinematics
– Systematic uncertainties
– χ^2 fit and final results
– $p + Be \rightarrow K^+ + X$ Cross-Section and Application of Result

Event Display



Select high energy ν events



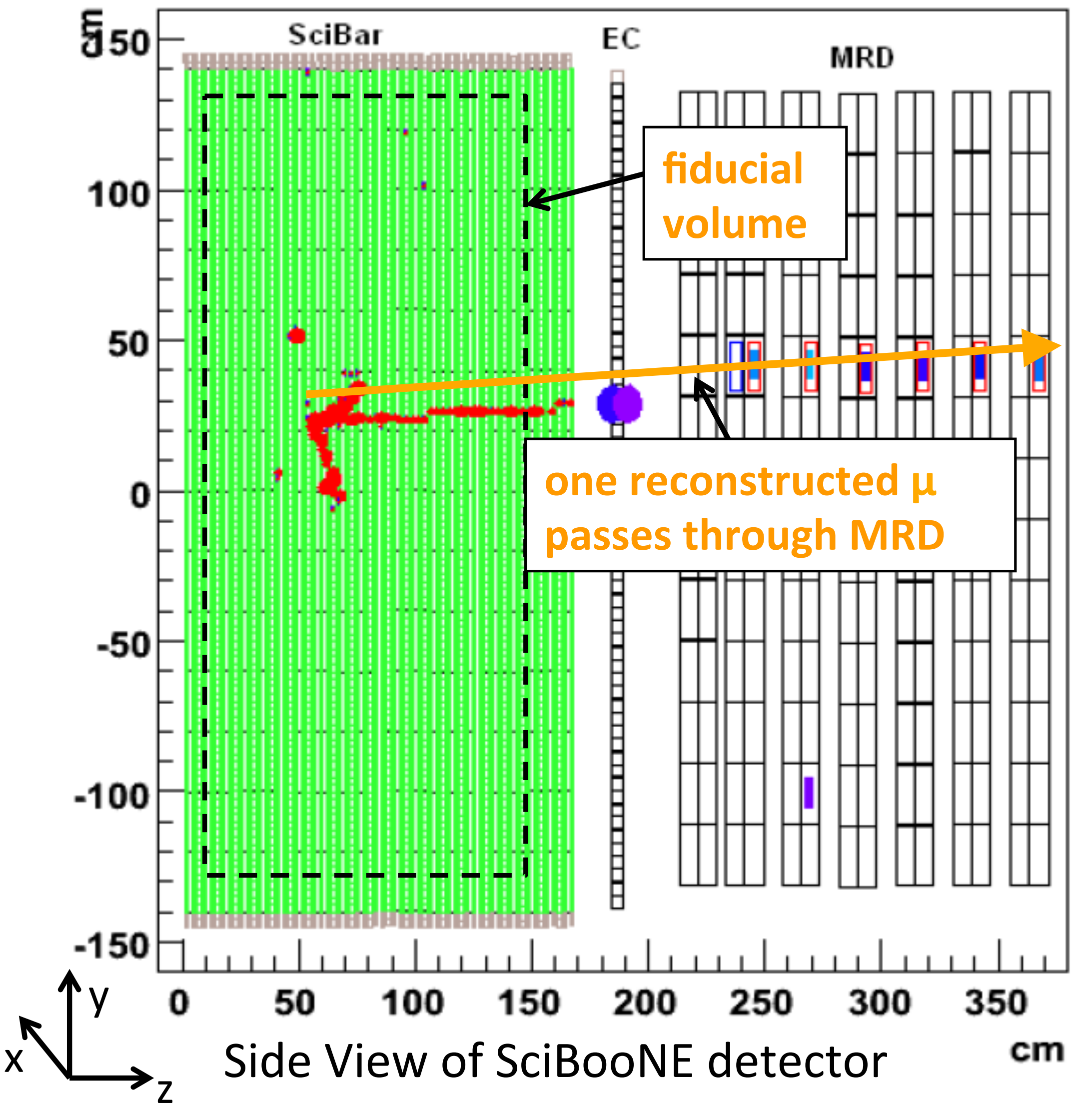
Side View of SciBooNE detector

- Search for events with a forward going μ that penetrates the SciBar and the MRD detector.
- High energy μ events come from a high energy ν_μ, which has a good probability to come from a K^+ decay.

SciBar-MRD Matched Events

- SciBar detector has a very good tracking, with high multiplicity and angular resolution for reconstructed tracks
- MRD detector is designed to have a very high efficiency to identify muons, muons that goes through the MRD detector need to have a momentum > 1.2 GeV
- Use both to identify high energy muons:
  - One SciBar track (neutrino target) matched in time and position to a MRD track (SciBar-MRD matched sample).

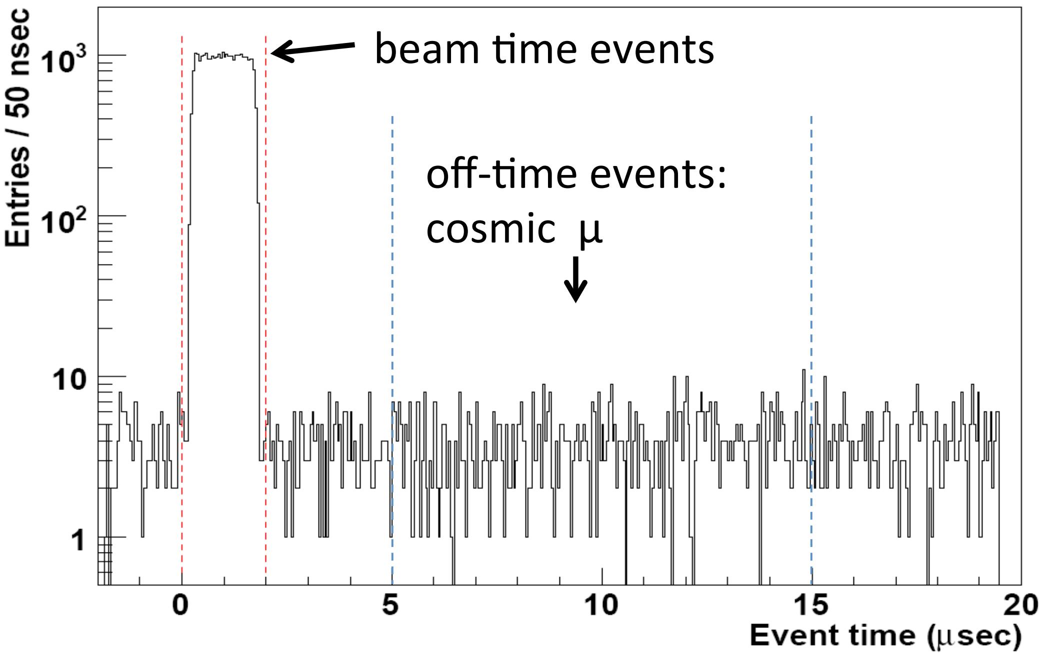
Analysis: Selection



Side View of SciBooNE detector

- The upstream edge of the track is within |x|,|y| ≤ 130 cm, and 5.24 ≤ |z| ≤ 149.34 cm
- Track must be in the time with the beam gate (0 to 2 μs).
- One and only one SciBar-MRD matched track.
  - **Energy reconstruction not possible events with energy > 1.2 GeV (not fully contained in the MRD).**

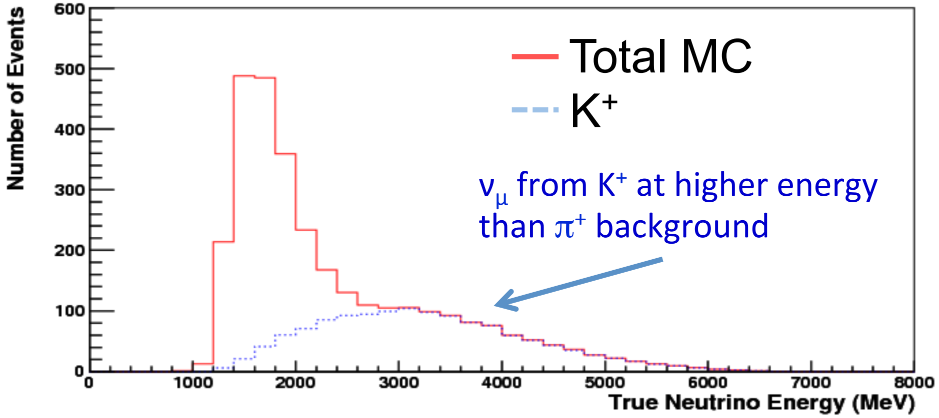
Analysis: Cosmic Events



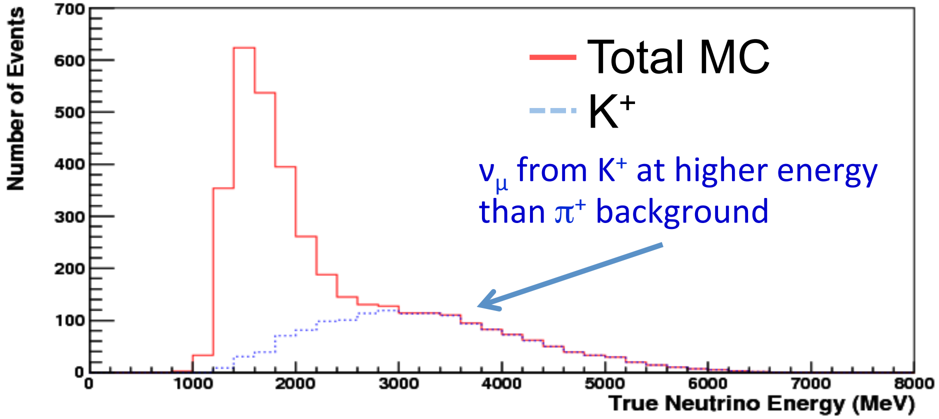
Event timing distribution of SciBar-MRD matched events. Dashed red lines indicate the 2 μsec beam timing window. Dashed blue lines indicate the 10 μsec off timing background window.

- SciBooNE is unshielded so it is constantly showered with cosmic muons.
- After all the selection cuts, there is still a small background in the data that comes from cosmic μ.
- Data taken from outside the beam time window is subtracted from beam time data. The off-time window is 5 times longer for adequate statistics.

Analysis: Selected Events in ν Mode



NUANCE prediction of true ν energy of selected events, normalized to POT, in neutrino mode.



NEUT prediction of true ν energy of selected events, normalized to POT, in neutrino mode.

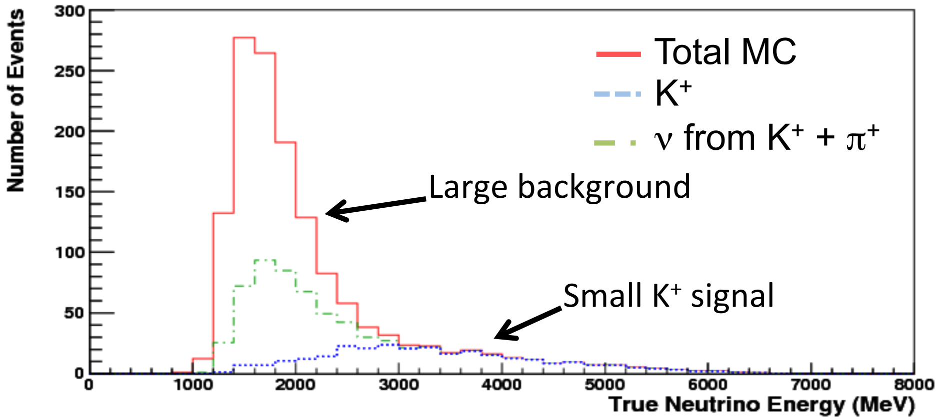
- Even after selecting for high energy μ events, π^+ background remains.

Need to use other variables to isolate K^+ neutrinos.

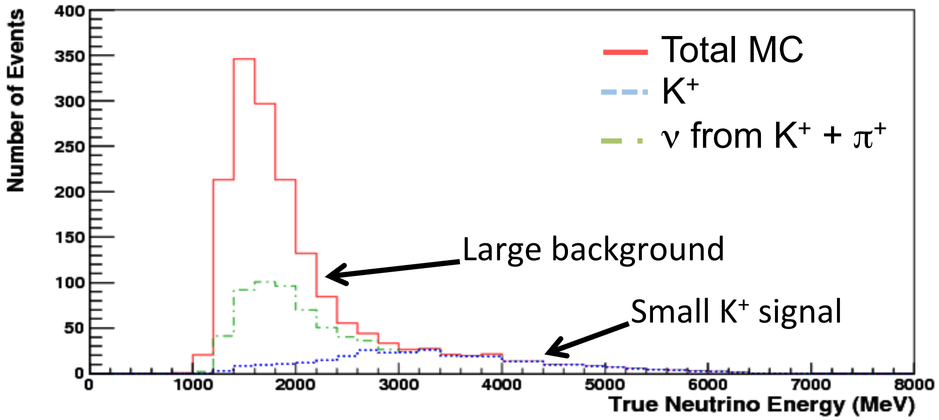
- For neutrino mode running:

	NUANCE	NEUT
Data	3188	
MC	3053	3656
ν_μ from K^+	1313	1517
ν_μ from π^+	1666	2050

Analysis: Selected Events in $\overline{\nu}$ Mode



NUANCE prediction of true ν energy of selected events, normalized to POT, in antineutrino mode.



NEUT prediction of true ν energy of selected events, normalized to POT, in antineutrino mode.

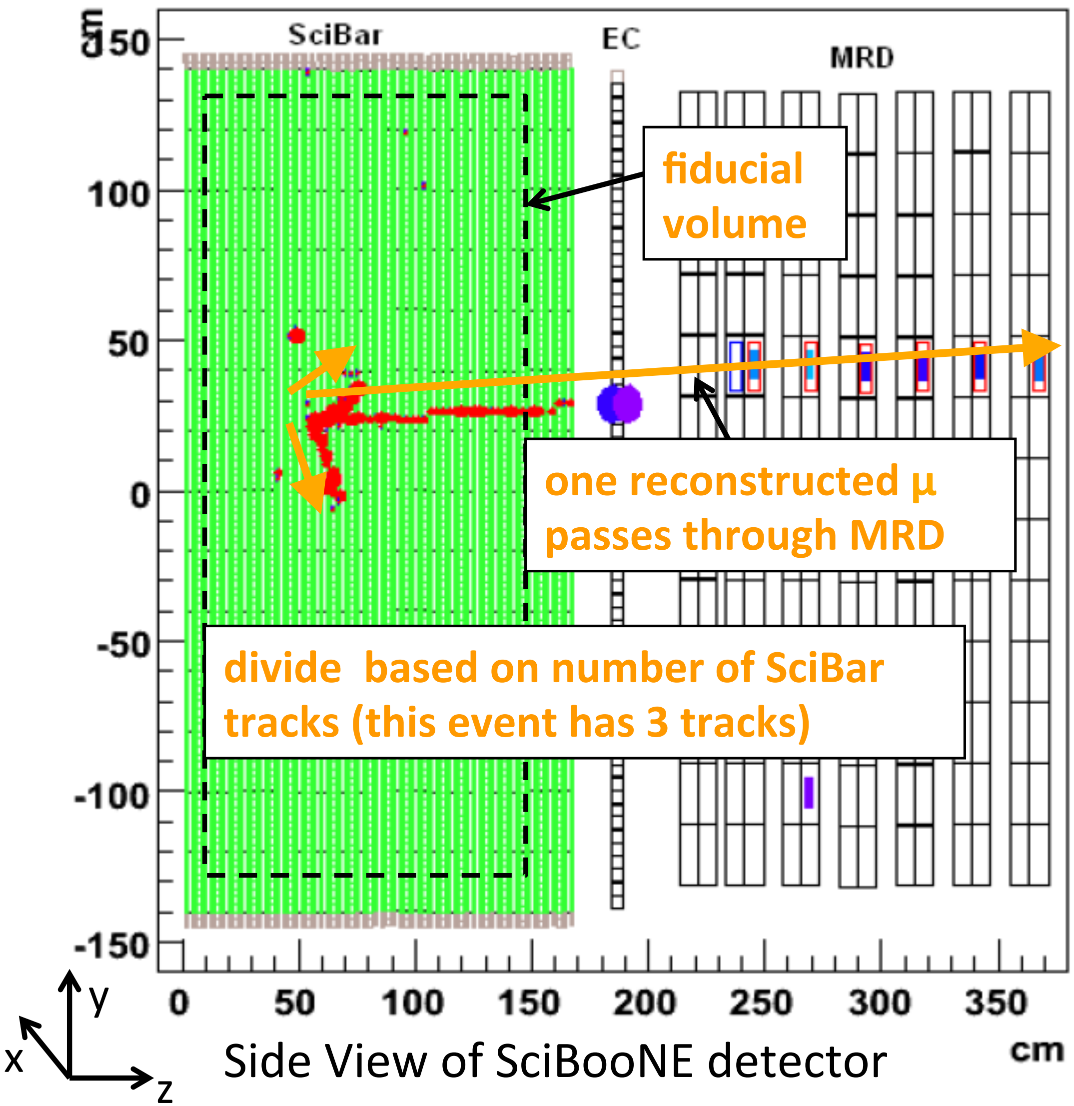
- The overall statistics are lower compared to ν mode running.
- Larger backgrounds. Additional background μ^+ (from $\overline{\nu}_\mu$ from π^-), which is indistinguishable from μ^- in detector.

Need to use other variables to isolate K^+ neutrinos

- For antineutrino mode running:

	NUANCE	NEUT
Data	1728	
MC	1389	1637
ν_μ from K^+	283	311
ν_μ from π^+	375	432
$\overline{\nu}_\mu$ from π^-	691	847

Analysis: Selection

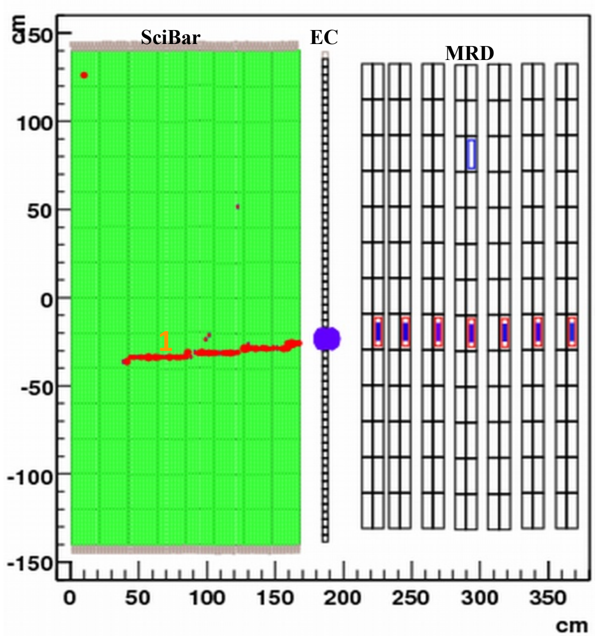


Side View of SciBooNE detector

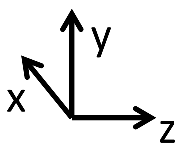
- Additional cut based on multiplicity: divide selected events into three samples based on number of SciBar tracks in event: 1,2,3.
- The different samples have different ν energy distributions, and hence, different signal to background ratios:
  - 1-track: lowest ν energy and signal/background
  - 2-track: intermediate ν energy and signal/background
  - 3-track: highest ν energy and signal/background

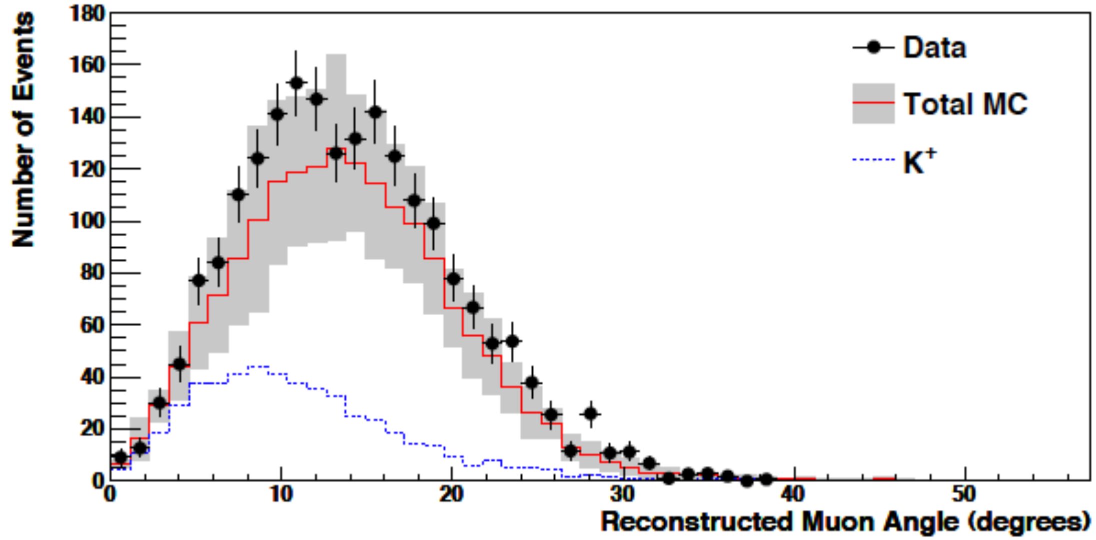
Analysis: 1 track events

Side View of SciBooNE detector



Event with 1 SciBar Track



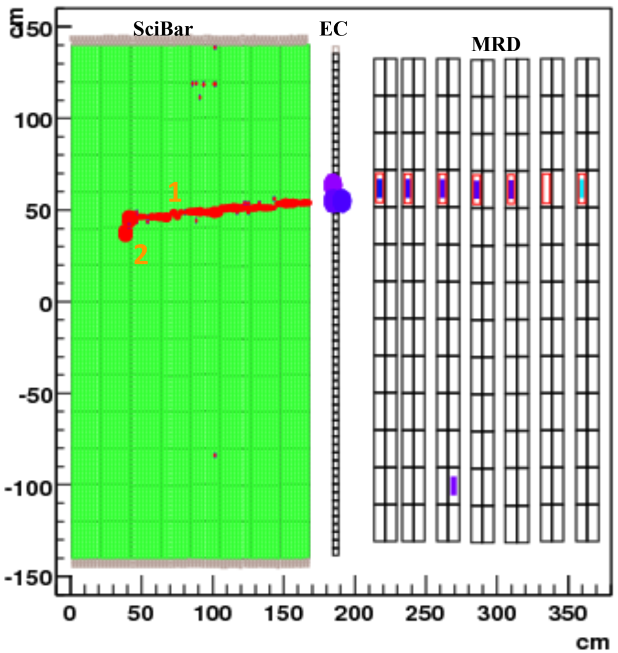


	1-track	2-track	3-track
ν_μ from K^+	30%	52%	76%
ν_μ from π^+	67%	46%	22%

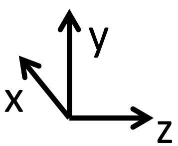
	K^+ Energy(GeV)	K^+ Angle(rad)
1 track	3.6	0.075
2-track	3.8	0.071
3-track	4.1	0.068

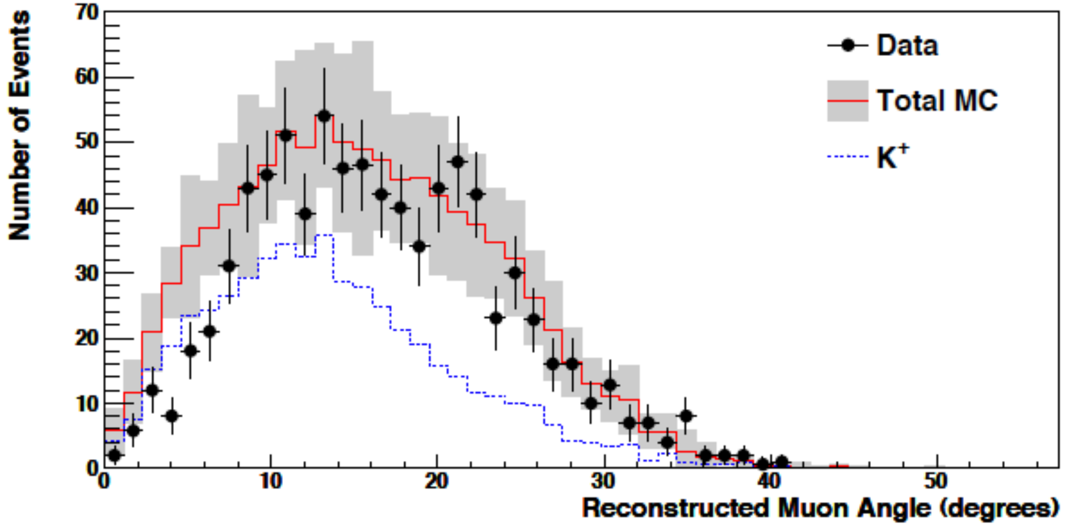
Analysis: 2 track events

Side View of SciBooNE detector



Event with 2 SciBar Tracks





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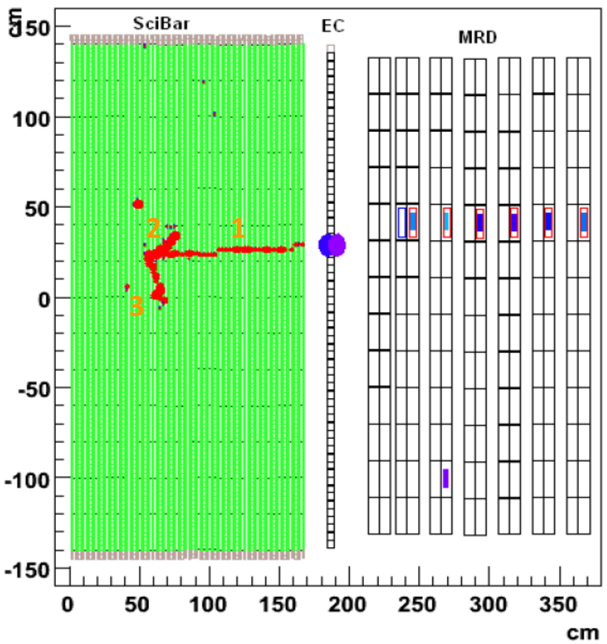
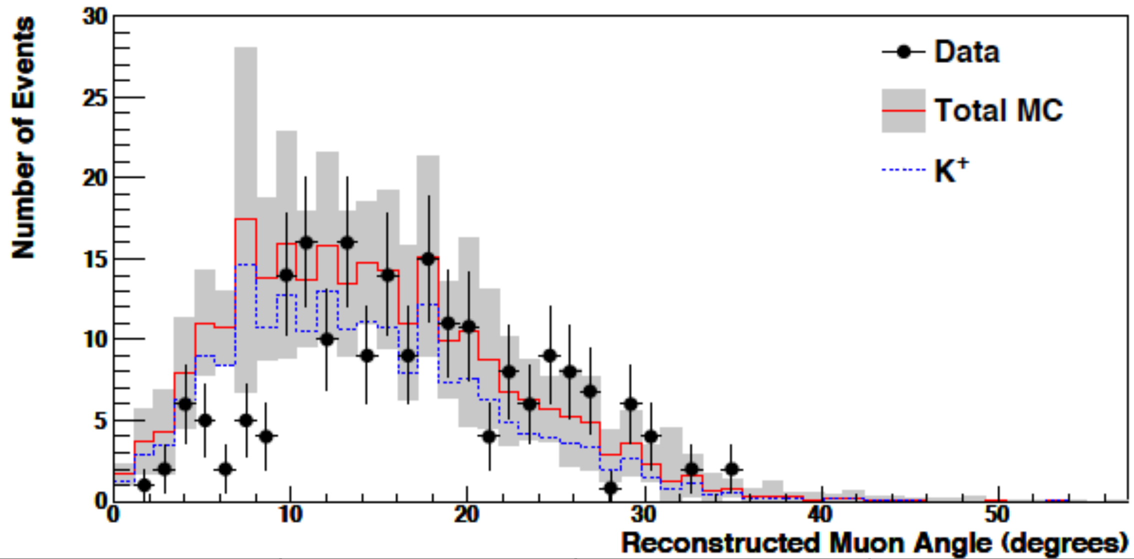
Analysis: 3 track events

Side View of SciBooNE detector



Event with 3 SciBar Tracks



	1-track	2-track	3-track
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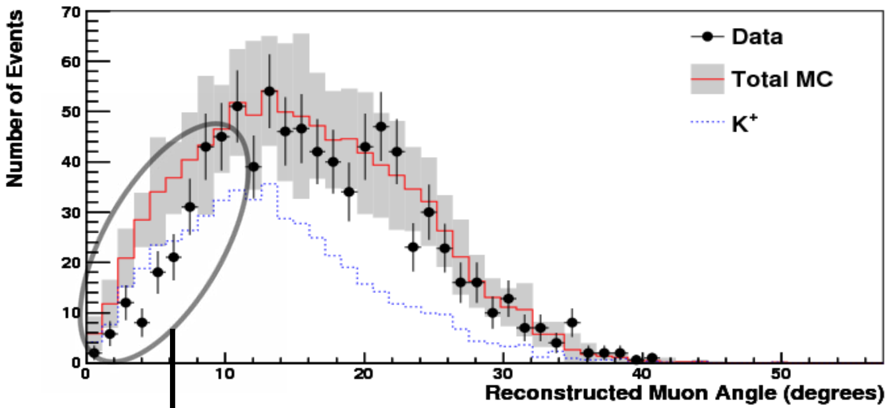
	K^+ Energy(GeV)	K^+ Angle(rad)
1 track	3.6	0.075
2-track	3.8	0.071
3-track	4.1	0.068

Analysis: Summary

- Select high energy muons requiring a forward track that penetrates the full MRD detector
- Split selected sample based on number of reconstructed SciBar tracks.
  - The different samples will have different ν energies.
- Use the difference in the muon angle distribution between neutrino events from K^+ and π^+ as criteria to extract and isolate K^+ events
  - The angular distributions of the μ from neutrinos coming from K^+ decay will be more forwardly peaked (smaller angles) than those events from neutrino coming from $\pi^\pm$ decay.
- Energy for muons or νs can't be used: most of the events penetrate MRD so only lower energy limits are available

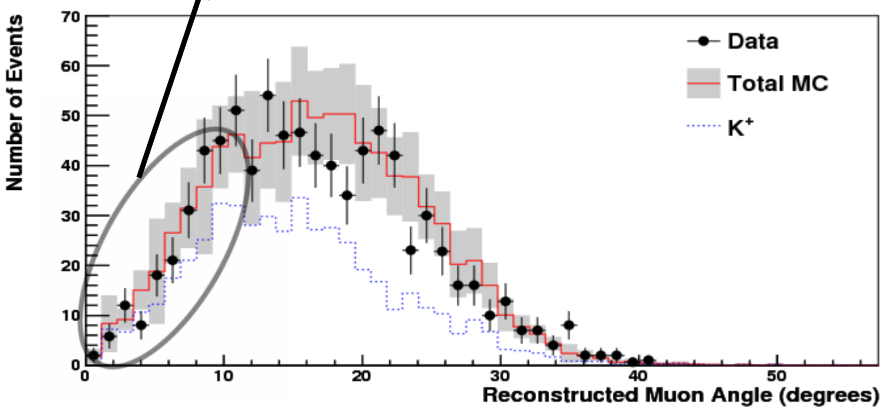
A nuclear model discrepancy

MC normalized to POT



NUANCE 2-track in neutrino mode

discrepancy between NUANCE and NEUT at low muon angle



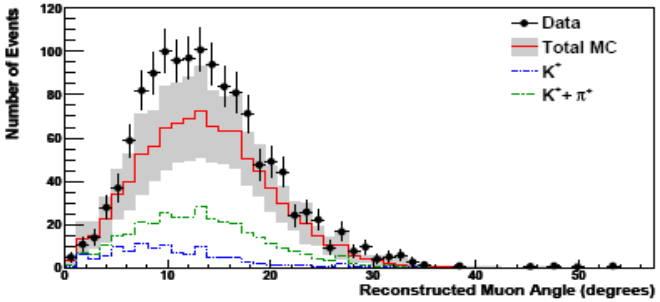
NEUT 2-track in neutrino mode

- Discrepancy is partly caused by the nuclear effect of proton emissions following π absorption in the nucleus after initial neutrino interaction. The effect, which is confirmed by previous measurements, is implemented in the MC.

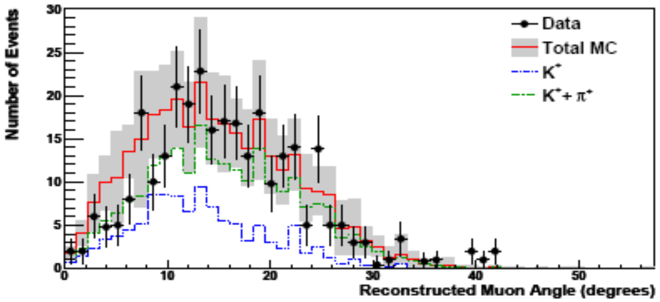
- The discrepancy is treated as a systematic uncertainty. We turned off and on the nuclear model in both NEUT and NUANCE and we assign as systematic error the largest variation.

Anti-Neutrinos sample

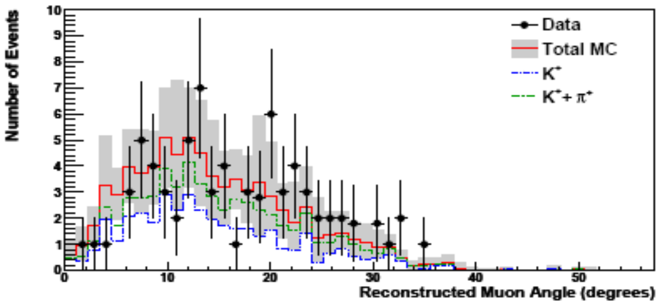
MC normalized to POT



NUANCE 1-track in antineutrino mode



NUANCE 2-track in antineutrino mode



NUANCE 3-track in antineutrino mode

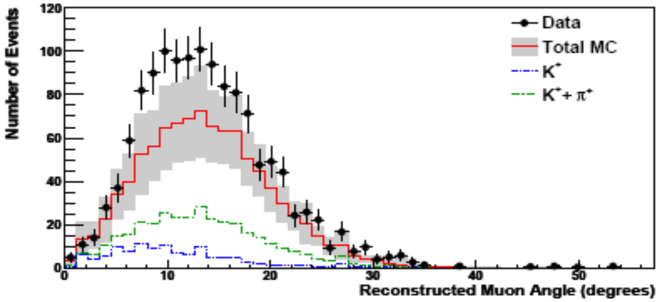
	1-track	2-track	3-track
ν_μ from K^+	12%	24%	55%
ν_μ from π^+	32%	38%	26%
$\bar{\nu}_\mu$ from π^-	49%	26%	20%

- Systematic uncertainties are relatively larger in $\bar{\nu}$ mode compared to ν mode.

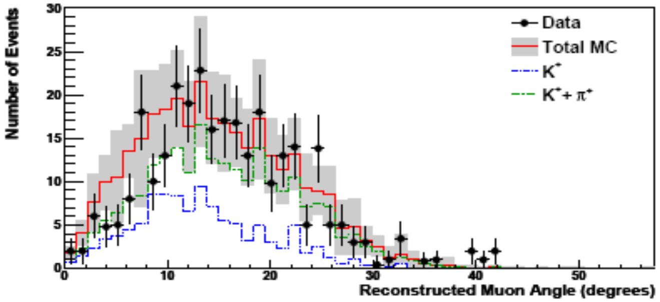
- Neutrino events from K^+ and π^+ are background in this sample, coming from K^+ and π^+ going straight down the horn, impossible to defocus

Anti-Neutrinos sample

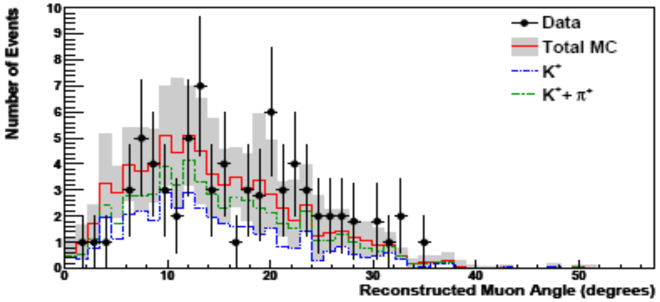
MC normalized to POT



NUANCE 1-track in antineutrino mode



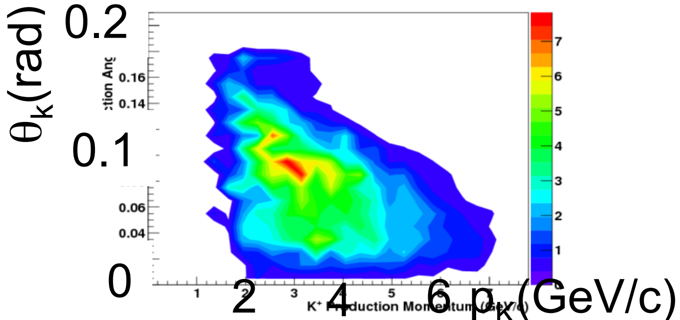
NUANCE 2-track in antineutrino mode



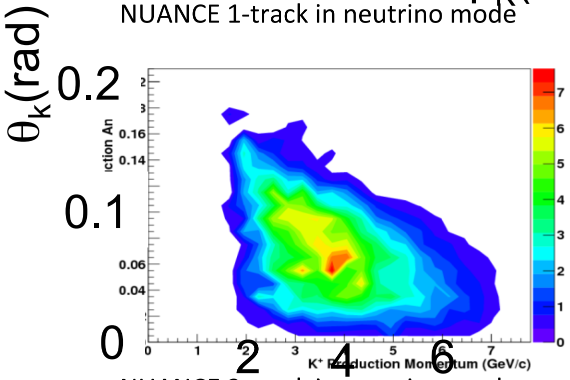
NUANCE 3-track in antineutrino mode

Anti-neutrino Sample	**K^+ Energy(GeV)**	**K^+ Angle(rad)**
1 track	4.1	0.042
2-track	4.4	0.033
3-track	4.6	0.028

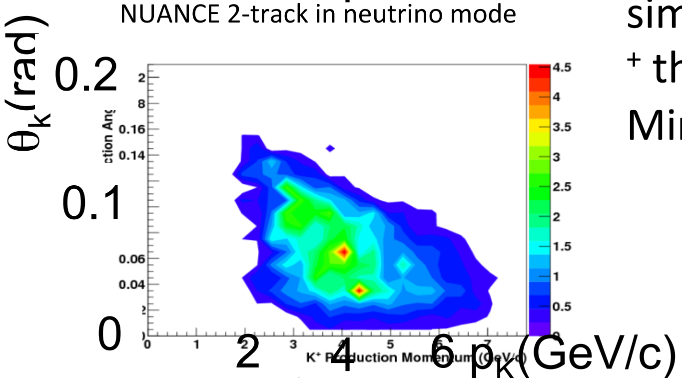
K^+ Phase Space for neutrino events



NUANCE 1-track in neutrino mode

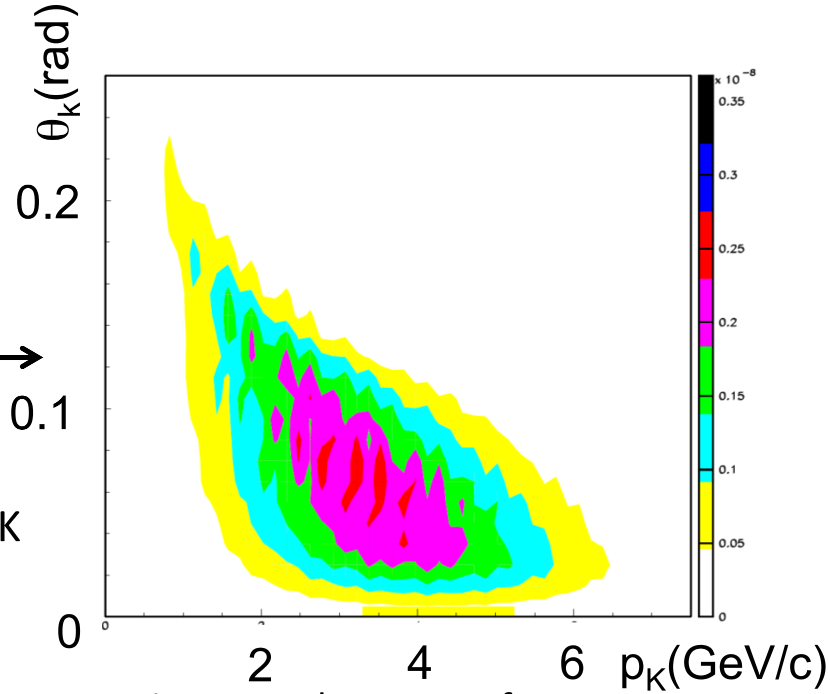


NUANCE 2-track in neutrino mode



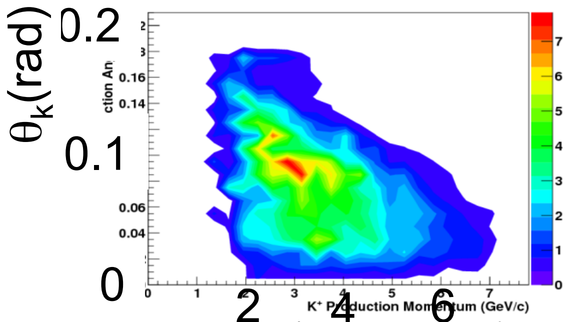
NUANCE 3-track in neutrino mode

The kinematics for K^+ selected in SciBooNE are similar to the kinematics of K^+ that produce ν_e events in MiniBooNE

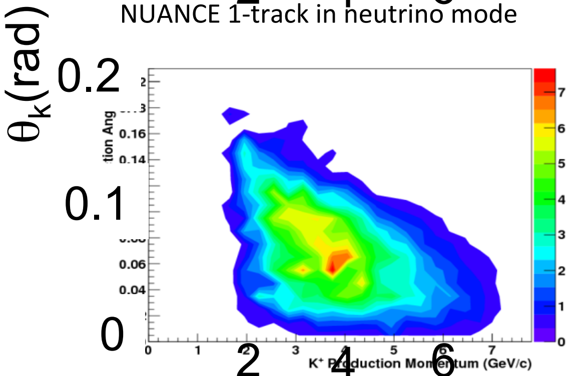


Kinematical region as function of angle and momentum for the K^+ mesons that produce ν_e events in MiniBooNE

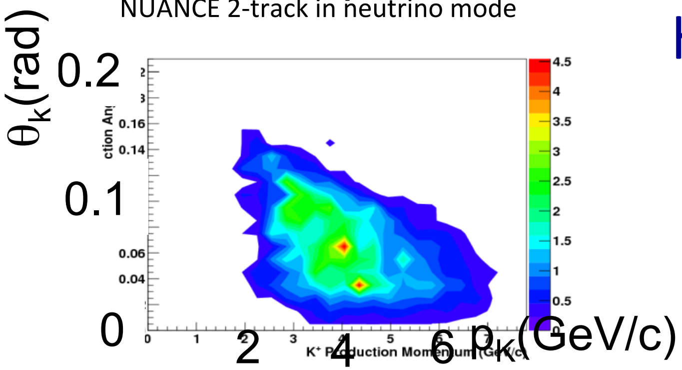
K^+ Phase Space for all selected events



NUANCE 1-track in neutrino mode



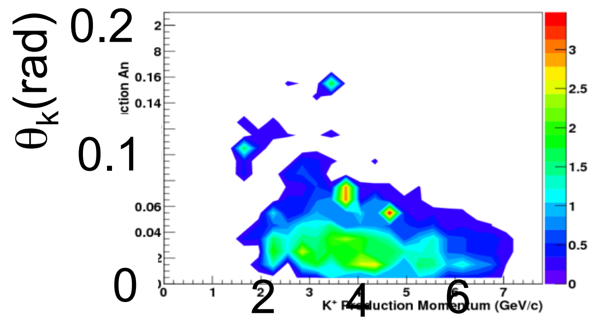
NUANCE 2-track in neutrino mode



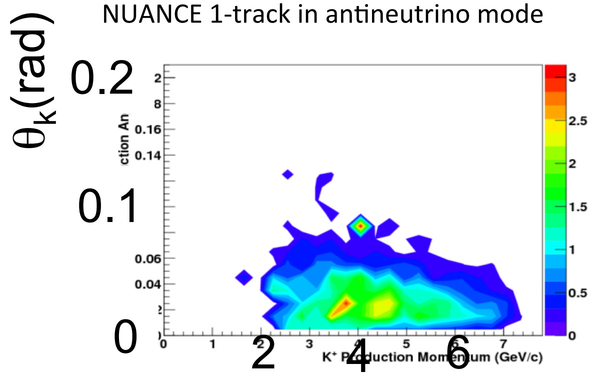
NUANCE 3-track in neutrino mode

Mean E_K^+/θ_K^+	E_K^+ (GeV)	θ_K^+ (°)
ν mode 1-track	3.6	4.3
ν mode 2-track	3.8	4.1
ν mode 3-track	4.1	3.9
$\bar{\nu}$ mode 1-track	4.1	2.4
$\bar{\nu}$ mode 2-track	4.4	1.9
$\bar{\nu}$ mode 3-track	4.6	1.6

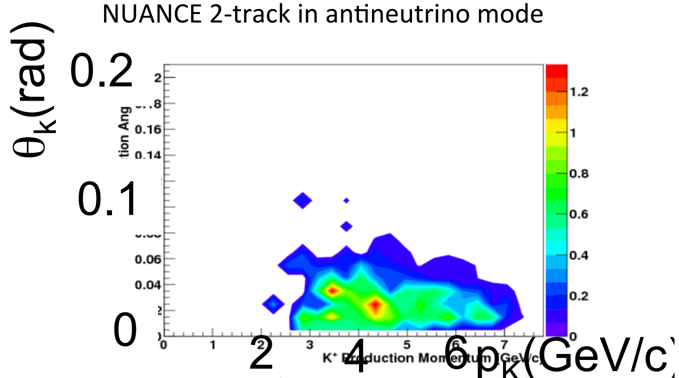
Energy for the neutrino coming from K^+ decay is higher in the antineutrino sample, and the angle is more forwardly peaked.



NUANCE 1-track in antineutrino mode



NUANCE 2-track in antineutrino mode



NUANCE 3-track in antineutrino mode

Systematic Uncertainties

- The systematic uncertainties can be classified into three categories: Beam, Cross-section (includes nuclear modeling), and Detector.

- Beam:
  - $\pi^{\pm}$ production uncertainties determined by spline fits to HARP data
  - Uncertainties in primary beam optics, secondary hadronic interactions in Be target and horn, and magnetic horn modeling

- Cross-section:
  - Axial mass uncertainties in neutrino charged current quasi-elastic interactions, charged current single resonant π production interactions, charged current multi-π production/deep inelastic scattering interactions

Systematic Uncertainties

- Uncertainty in π interactions in the nucleus after initial neutrino interaction: absorption, charge exchange, inelastic scattering
- Proton emissions associated with π absorption in nucleus. The uncertainty was obtained by turning on/off this nuclear model in NEUT and taking the variation as uncertainty.

- Detector:
  - Multi-anode photomultiplier tube cross-talk and resolution uncertainties
  - Scintillator quenching uncertainty
  - Conversion uncertainty from ADC counts to photoelectron
  - TDC deadtime uncertainty

Analysis: χ^2 Fit

Minimize the following χ^2 function:

$$\chi^2 = \chi^2_{\nu} + \chi^2_{\bar{\nu}} =$$

$$\sum_{i,j}^{N} (N_i^{obs} - N_i^{pred})(V^{\nu}_{stat} + V^{\nu}_{sys})^{-1}_{ij}(N_j^{obs} - N_j^{pred}) +$$

$$\sum_{p,q}^{M} (M_p^{obs} - M_p^{pred})(V^{\bar{\nu}}_{stat} + V^{\bar{\nu}}_{sys})^{-1}_{pq}(M_q^{obs} - M_q^{pred})$$

- N, M are the muon angle bins for the 1,2,3-track samples in neutrino and antineutrino mode running, respectively.
- N^{obs}, M^{obs}: Data
- N^{pred}, M^{pred}: MC (function of K^+ normalization factor and ν cross-sections normalization factors)
- $V^{\nu}, V^{\bar{\nu}}$: covariance matrix computed using syst. described before

What are we fitting

- We fit the K^+ production ratio, defined as the ratio between the measured number of K^+ produced at the target and the Beam MC prediction:

$$R_{K^+}^{\mathrm{Prod}} = \frac{\left.\frac{d^2\sigma}{dp\,d\Omega}\right|_{MC}}{\left.\frac{d^2\sigma}{dp\,d\Omega}\right|_{Data}}$$

$$\left.\frac{d^2\sigma}{dp\,d\Omega}\right|_{MC} = (6.303 \pm 2.017)\,mb/(GeV/c \times sr)$$

- Measurement is done using three samples (slightly different K^+ kinematics):
    - Neutrino
    - Antineutrino
    - Neutrino + Antineutrino

What are we fitting and results

$$R_{K^+} = \frac{\left.\frac{d^2\sigma}{dpd\Omega}\right|_{MC}}{\left.\frac{d^2\sigma}{dpd\Omega}\right|_{Data}} = 0.848 \pm 0.120$$

$$\times$$

$$\left.\frac{d^2\sigma}{dpd\Omega}\right|_{MC} = (6.303 \pm 2.017) mb / (GeV / c \times sr)$$

$$\downarrow$$

$$\boxed{\left.\frac{d^2\sigma}{dpd\Omega}\right|_{\nu+\bar{\nu}} = 5.34 \pm 0.76 \text{ mb/(GeV/c x sr) @ } \left\langle E_{K^+} = 3.9 GeV \right\rangle and \left\langle \theta_{K^+} = 0.06 rad \right\rangle}$$

$$\left.\frac{d^2\sigma}{dpd\Omega}\right|_{\nu} = 5.77 \pm 0.83 \text{ mb/(GeV/c x sr) @ } \left\langle E_{K^+} = 3.8 GeV \right\rangle and \left\langle \theta_{K^+} = 0.07 rad \right\rangle$$

$$\left.\frac{d^2\sigma}{dpd\Omega}\right|_{\bar{\nu}} = 3.18 \pm 1.94 \text{ mb/(GeV/c x sr) @ } \left\langle E_{K^+} = 4.3 GeV \right\rangle and \left\langle \theta_{K^+} = 0.05 rad \right\rangle$$

K^+ Results using two neutrino x-sect MCs

K^+ normalization factor relative to MC with NUANCE prediction

	ν-mode	**$\bar{\nu}$-mode**	**Combined $\nu+\bar{\nu}$**
K^+ Production	0.89±0.04±0.12	0.54±0.09±0.32	$\boxed{0.85\pm0.04\pm0.11}$
χ^2/dof	47.8/45	18.5/27	67.3/79

K^+ normalization factor relative to MC with NEUT prediction

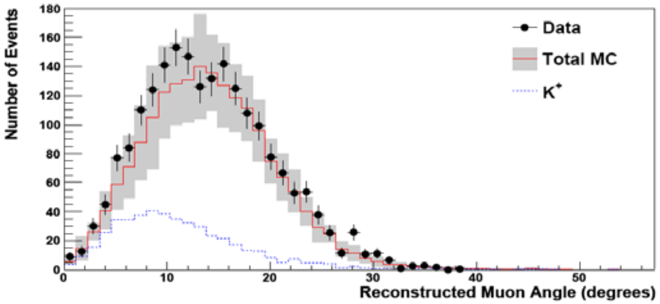
	ν-mode	**$\bar{\nu}$-mode**	**Combined $\nu+\bar{\nu}$**
K^+ Production	0.90±0.05±0.13	0.77±0.12±0.31	$\boxed{0.87\pm0.05\pm0.11}$
χ^2/dof	40.6/45	17.7/26	58.9/77

The close corresponding values between the NUANCE and NEUT results show the robustness of the analysis and demonstrate the independency of the result with respect to the underlying neutrino cross-sections and nuclear models.

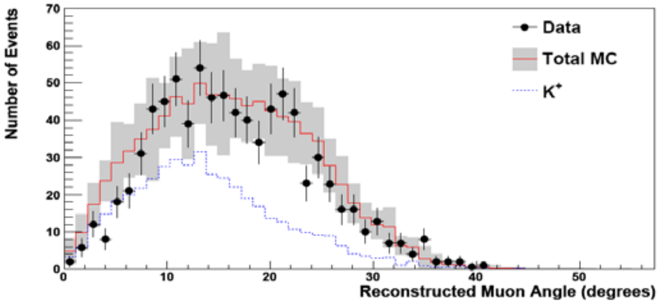
Value of the χ^2/dof shows a better agreement with NEUT as it can be see in the next slide

$$\frac{d^2\sigma}{dp d\Omega} = 5.34 \pm 0.76 \text{ mb/(GeV/c x sr) @ } \left\langle E_{K^+} = 3.9GeV \right\rangle and \left\langle \theta_{K^+} = 0.06rad \right\rangle$$

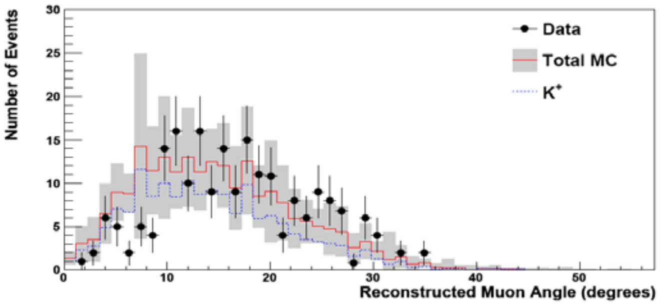
Angular distribution after χ^2 Fit



NUANCE 1-track in neutrino mode after fit



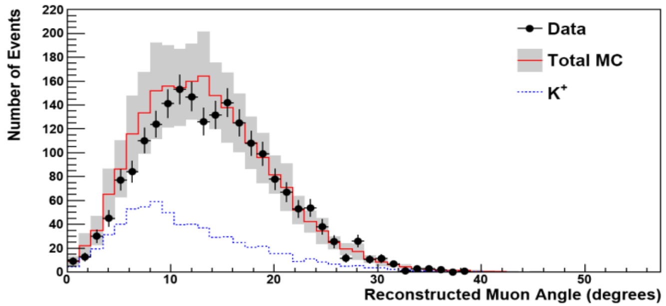
NUANCE 2-track in neutrino mode after fit



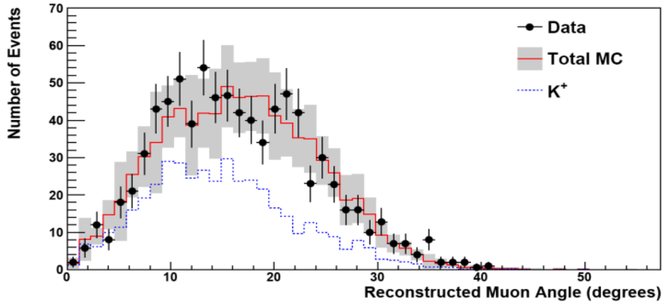
NUANCE 3-track in neutrino mode after fit

The K^+ combined production factor and the ν cross-section central values for NUANCE(NEUT) has been applied to the NUANCE(NEUT) MC predictions.

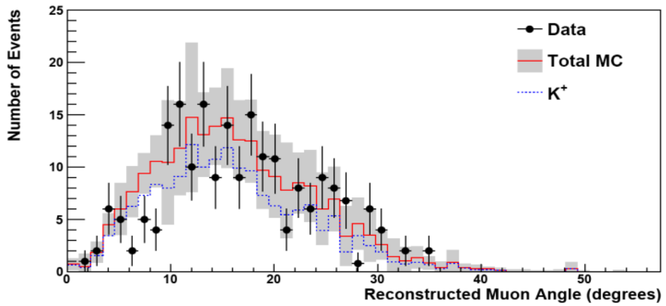
Grey is the systematic uncertainties



NEUT 1-track in neutrino mode after fit



NEUT 2-track in neutrino mode after fit

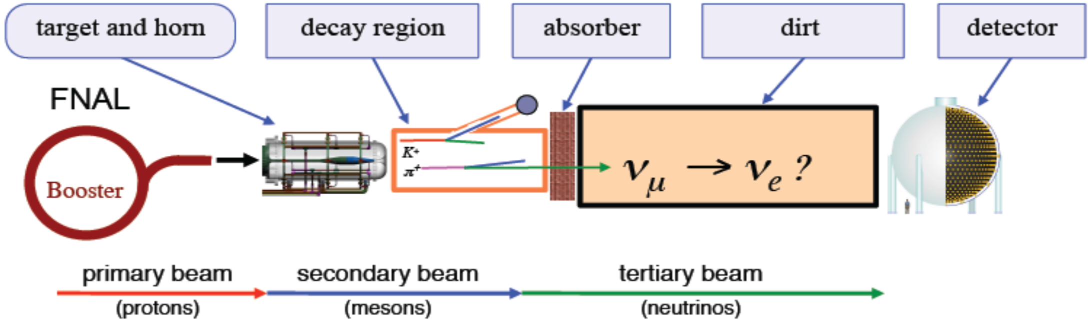


NEUT 3-track in neutrino mode after fit

- Kaon Production
  - SciBooNE measurement
- ν_e Backgrounds for Oscillation experiments
  - why is hard to isolate and measure ν_e and ν_μ from Kaons
- Predicting Kaon production at low energies:
  - Feynman Scaling model
  - Fit to available data
  - Include SciBooNE measurement
  - Constraining K^+ production will reduce MiniBooNE error

ν_e appearance experiment

Looking for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ like in the MiniBooNE experiment



Oscillation signature is charged-current quasi-elastic scattering:

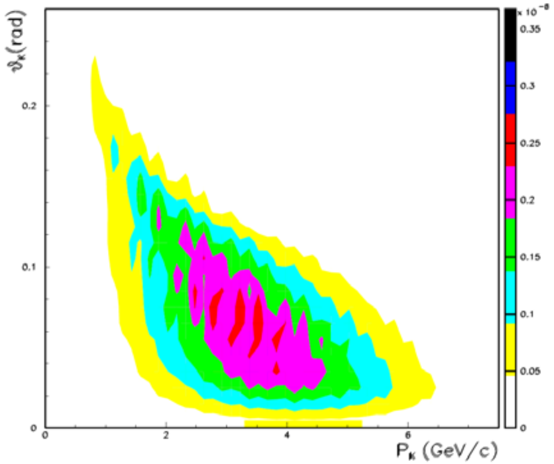
- Dominant backgrounds to oscillation:
  - Intrinsic ν_e in the beam
    $\pi \rightarrow \mu \rightarrow \nu_e$
    $K^+ \rightarrow \pi^0 e^+ \nu_e$, $K^0 \rightarrow \pi^0 e^\pm \nu_e$
  - Particle misidentification in detector
    - Neutral current resonance:
    $\Delta \rightarrow \pi^0 \rightarrow \gamma\gamma$ or $\Delta \rightarrow n\gamma$, mis-ID as e

Background to ν_e appearance searches

- Intrinsic ν_e contamination in the neutrino beam
  - High energy contribution comes from Kaon decays
- NC π^0 events - two gammas can simulate an electron interaction in the detector, similar signature to the ν_e interaction

- Muon Decays: Contributes ≈56% of ν_e content and peaks in the peak energy region
- Charged Kaon Decays: Peaks outside the beam peak energy region, but contributes about 34% of the ν_e content
- Neutral Kaon Decays: Contributes about 10% of the ν_e content but is one of the less well understood backgrounds

Kinematical region as function of angle and momentum for the K^+ mesons that produce ν_e events in MiniBooNE



- Kaon Production
  - SciBooNE measurement
- ν_e Backgrounds for Oscillation experiments
  - why is hard to isolate and measure ν_e and ν_μ from Kaons
- Kaon production at low energies:
  - Feynman Scaling model
  - Fit to available data
  - SciBooNE constraint
  - Include SciBooNE measurement
  - Constraining K^+ production will reduce MiniBooNE error

Feynman Scaling formalism

We need a parameterization to describe inclusive production of secondary K^+ mesons in proton-Beryllium collision for experiment with low primary beam momentum.

$$p + Be \rightarrow K^+ + X$$

The parameterization is based on Feynman scaling in which the invariant cross section is described as a function of transverse momentum, p_T , and a scaling variable

$$x_F = \frac{p_{\parallel}^{CM}}{p_{\parallel}^{CM\max}}$$

Produced Hadron	Exclusive Reaction	M_X (GeV/c^2)	$\sqrt{s_{thresh}}$ (GeV)	E_{thresh}^{beam} GeV
π^+	$pn\pi^+$	1.878	2.018	1.233
π^-	$pp\pi^+\pi^-$	2.016	2.156	1.54
π^0	$pp\pi^0$	1.876	2.011	1.218
K^+	$\Lambda^0 pK^+$	2.053	2.547	2.52
K^-	ppK^+K^-	2.37	2.864	3.434
K^0	$p\Sigma^+K^0$	2.13	2.628	2.743

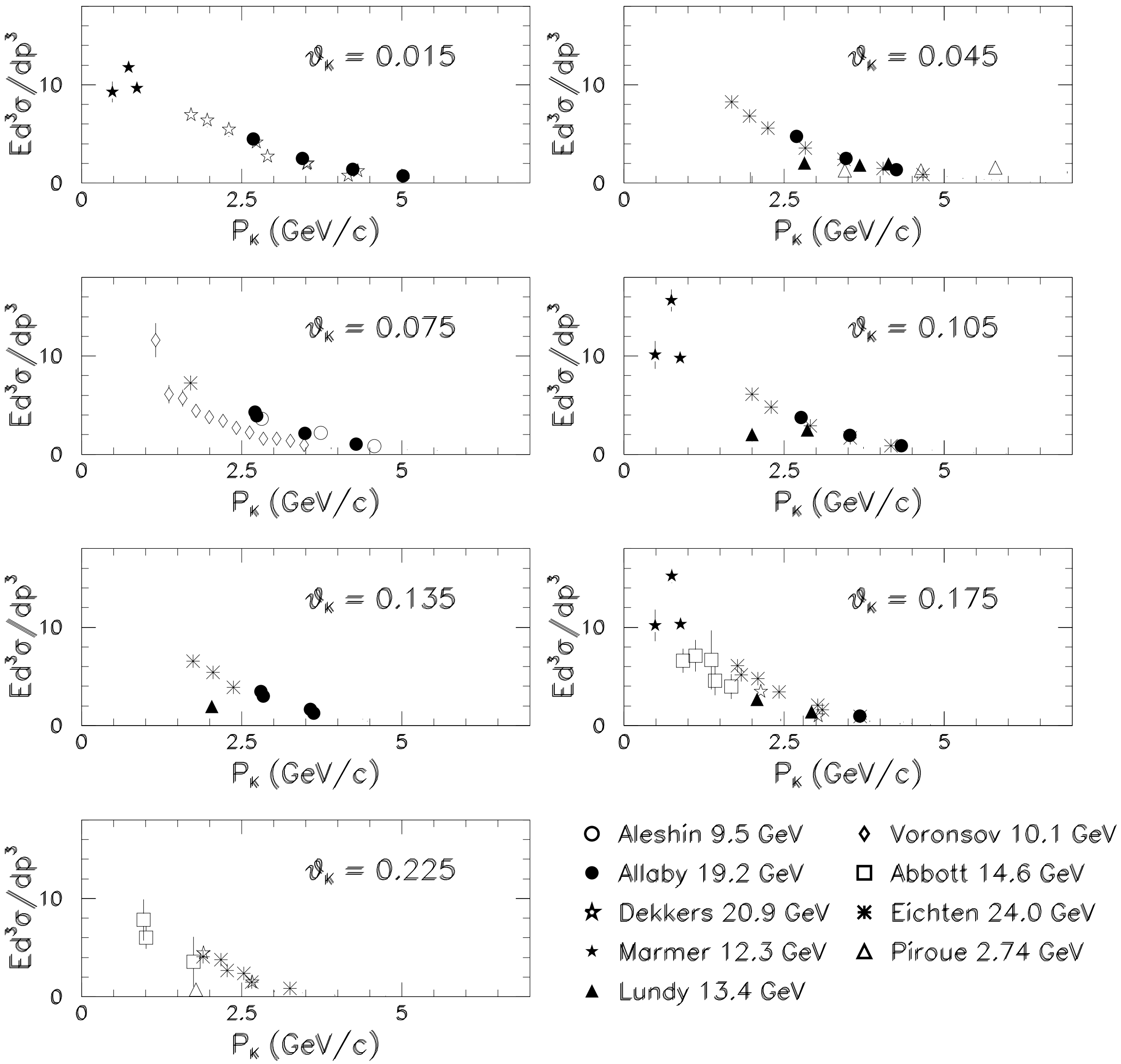
depends upon the particle being produced and it is derived from exclusive channel

$$E\frac{d^3\sigma}{dp^3} = AF\left(x_F, p_t\right) \Rightarrow \frac{d^2\sigma}{dpd\Omega} = \frac{p^2}{E}E\frac{d^3\sigma}{dp^3} = \frac{p^2}{E}AF\left(x_F, p_t\right)$$

Available K^+ production data

K^+ Data Sets	P_{BEAM}(GeV)	P_K(GeV)	θ_K(degrees)	x_F	p_t(GeV)	σ_{Norm}
Abbott	14.6	$2-8$	20°–30°	$-0.12-0.07$	$0.2-0.7$	10%
Aleshin	9.5	$3-6.5$	3.5°	$0.3-0.8$	$0.2-0.4$	10%
Allaby	19.2	$3-16$	0°–7°	$0.3-0.9$	$0.1-1.0$	15%
Dekkers	18.8 , 23.1	$4-12$	$0^\circ, 5^\circ$	$0.1-0.5$	$0.0-1.2$	20%
Eichten	24.0	$4-18$	0°–6°	$0.1-0.8$	$0.1-1.2$	20%
Lundy	13.4	$3-6$	$2^\circ, 4^\circ, 8^\circ$	$0.1-0.6$	$0.1-1.2$	20%
Marmer	12.3	$0.5-1$	$0^\circ, 5^\circ, 10^\circ$	$-0.2--0.05$	$0.0-0.15$	20%
Piroue	2.74	$0.5-1$	$13^\circ, 30^\circ$	$-0.3-1.0$	$0.15-0.5$	20%
Vorontsov	10.1	$1-4.5$	3.5°	$0.03-0.5$	$0.1-0.25$	25%

Available K^+ production data



For this plot, the data from each data set is converted first to x_F and p_T and then scaled to $p_K^{8.89}$ and $\theta_K^{8.89}$ for a 8.9 GeV/c beam momentum.

For example, given a cross section point at p_{BEAM}=20 GeV/c with a given p_K and θ_K, one can calculate the x_F and p_T for this point. One can then find the equivalent p'_K and θ'_K that would have the same x_F and p_T at p_{BEAM}=8.9 GeV/c.

As seen from the plots, the data appears to obey the scaling hypothesis reasonably well

Predicting Kaon Production

- Low energy neutrino beams like the BNB use 8.9 GeV protons and there is only precise data on Kaon Production above 20 GeV
  - Feynman Model can be used to describe the expected x_F and p_T dependence:

$$\frac{d^2\sigma}{dpd\Omega} = \left(\frac{p_K^2}{E_K}\right) c_1 \times \exp\left[c_3 |x_F|^{c_4} - c_7 |p_T \times x_F|^{c_6} \underbrace{- c_2 p_T - c_5 p_T^2}\right] \quad with \quad \frac{d^2\sigma}{dpd\Omega} = 0 \;\; for \;\; |x_F| > 1$$

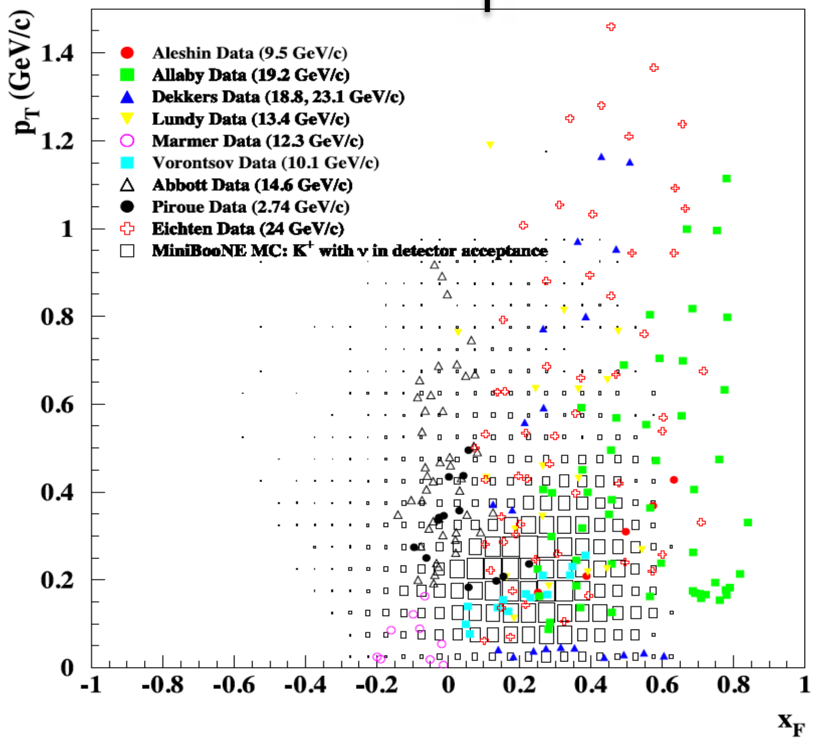
For the x_F dependence this kind of term is needed to have a flat rapidity plateau around x_F=0: $\exp(-a|x_F|^b)$

Allow some coupling between the x_F and p_T

The expectation of a limited p_T range is provided by including exponential moderating factors for powers of p_T

Feynman Scaling Fit

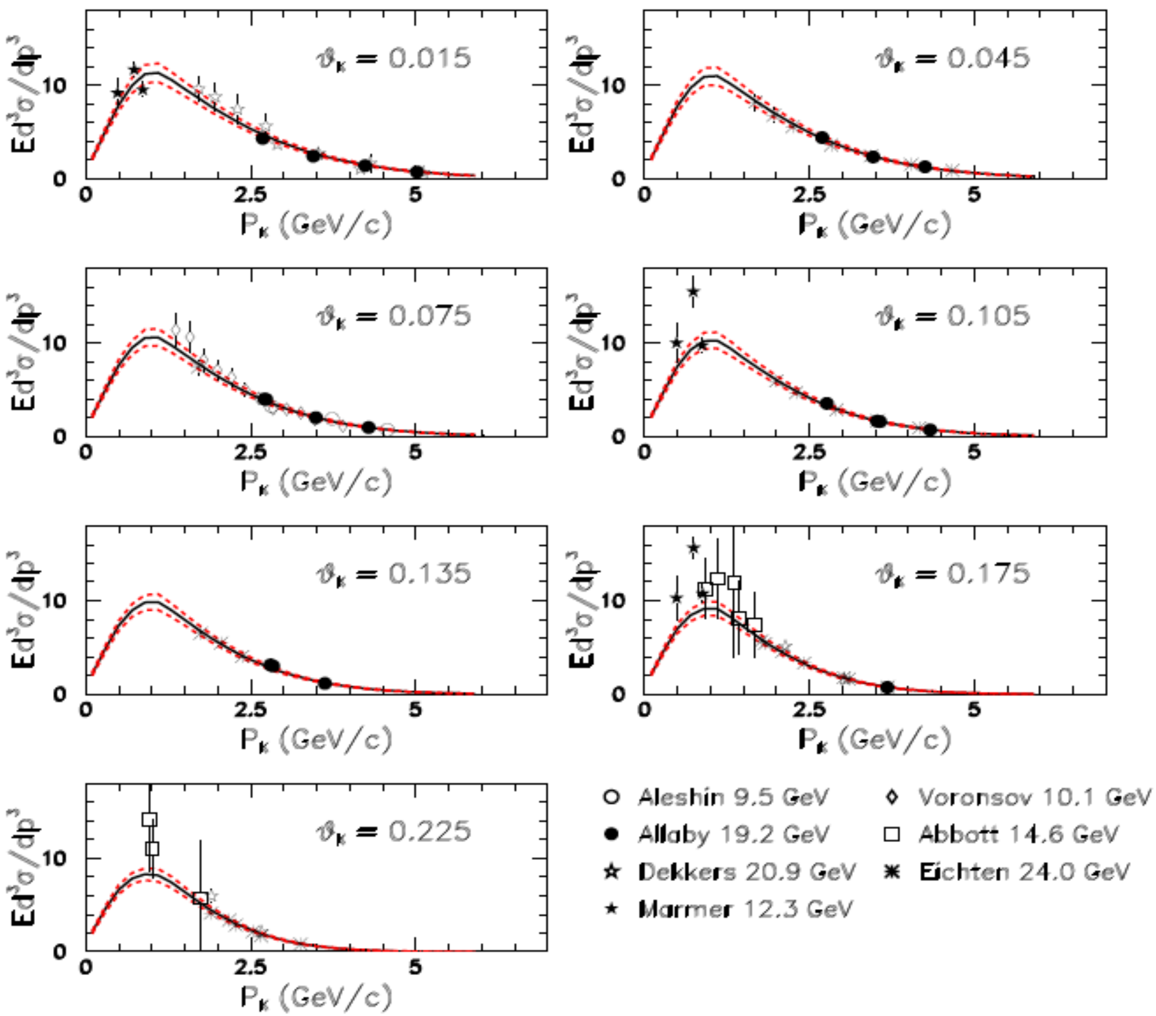
$$\chi_j^2 = \left[\sum_i \frac{(N_j \times SF_i - Data_i)^2}{(f \times \sigma_i)^2}\right] + \frac{(1-N_j)^2}{\sigma_{N_j}^2}$$



- i is the (p_K,θ_K) bin index,
- SF is the scaling function prediction evaluated at the given (p_{BEAM}, p_K,θ_K),
- $Data_i$ is the measurement at p_{BEAM}, p_K,θ_K,
- σ_i is the data error for measurement i,
- f is the scaling factor to bring the χ^2/d.o.f. = 1,
- N_j is the normalization factor for experiment j,
- σ^2_{Nj} is the normalization uncertainty for experiment j

Feynman Scaling Fit	$1.2< P_K^{8.89}(GeV/c) <5.5$ Value	Error	
c1	11.70	1.05	
c2	0.88	0.13	
c3	4.77	0.09	
c4	1.51	0.06	
c5	2.21	0.12	
c6	2.17	0.43	
c7	1.51	0.40	Input Error
Aleshin	1.09	0.07	0.10
Allaby	1.04	0.07	0.15
Dekkers	0.84	0.06	0.20
Vorontsov	0.53	0.04	5.00
Abbott	0.76	0.07	0.15
Eichten	1.00	0.07	0.15
χ^2/d.o.f. (no f)	2.28	($d.o.f. = 119$)	

Feynman Scaling: data agreement



Feynman Scaling fit + SciBooNE flux measurement

$$\frac{d^2\sigma}{dpd\Omega} = 5.34 \pm 0.76 \text{ mb/(GeV/c x sr)}$$

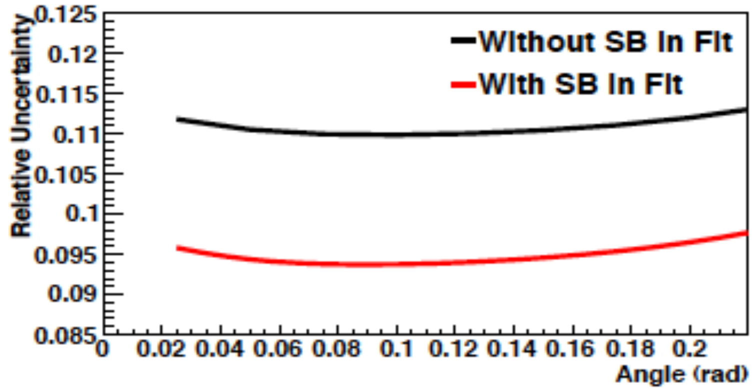
$$\left\langle E_{K^+} = 3.9GeV \right\rangle and \left\langle \theta_{K^+} = 0.06rad \right\rangle$$

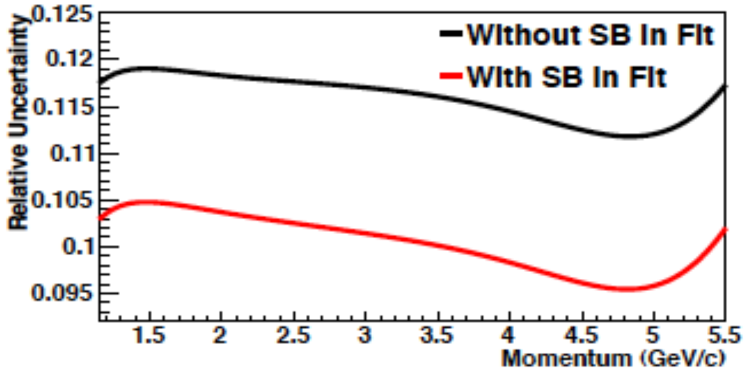
Adding SciBooNE measurement to the fit as

$$pull - term_{\nu,\bar{\nu}} = \frac{\left(\frac{N_i}{N_0} - K^+_{prod,SB}\right)}{\left(error\ K^+_{prod,SB}\right)^2}$$

$$N_i = \sum_i \frac{\frac{d^2\sigma}{dpd\Omega}(c_{fit}, \theta_i, p_i)}{\frac{d^2\sigma}{dpd\Omega}(c_{MC}, \theta_i, p_i)}$$

$$N_0 = \sum_i 1$$





- The Feynman Scaling model prediction of K^+ production at 8.9 GeV has been validated in two different ways:
  - Model prediction is in agreement with the SciBooNE measurement
  - SciBooNE measurement is now included in the list of data sets used for the Feynman Scaling fit

- The SciBooNE measurement helps reducing the error assumed by the MiniBooNE collaboration on the K^+ production at the BNB from 32% to 9%

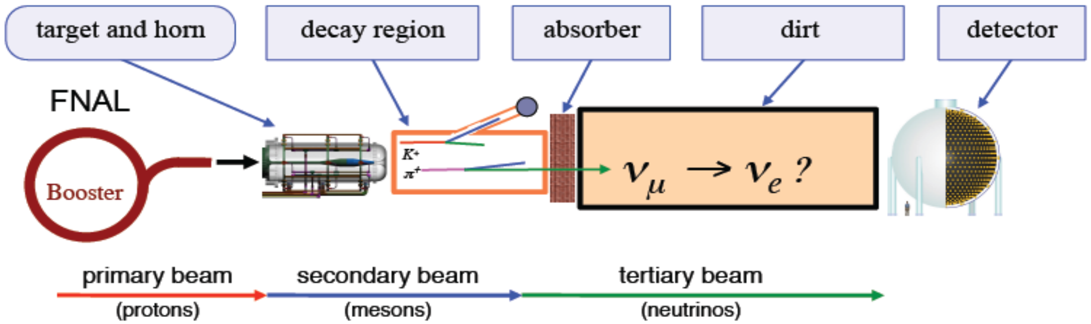
- SciBooNE experiment provide also a K^+ rate measurement defined as the K^+ production at the proton target times the neutrino cross-sections:

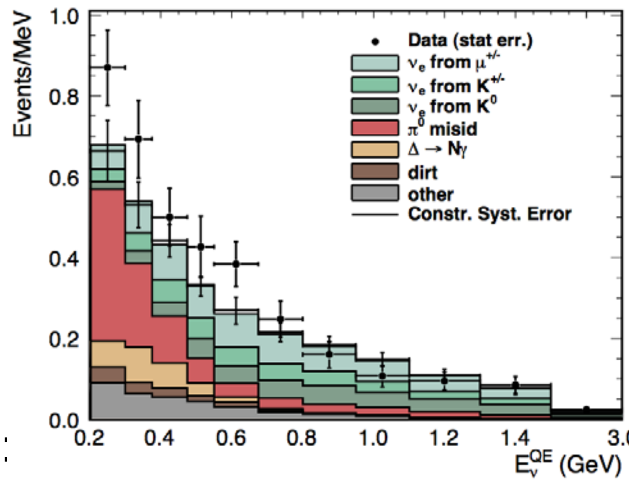
  - Can be used directly by MiniBooNE to constrain the intrinsic ν_e background from K^+

  - Can't be used by experiments with target material different from C because of the dependence on neutrino target (neutrino/antineutrino cross-sections on C)

Apply SciBooNE result to MiniBooNE

Looking for $\bar{\nu}_\mu \to \bar{\nu}_e$





Oscillation signature is charged-current quasi-elastic scattering:

- Dominant backgrounds to oscillation:
  - Intrinsic ν_e in the beam
    $\pi \to \mu \to \nu_e$
    $K^+ \to \pi^0 e^+ \nu_e$, $K^0 \to \pi^0 e^\pm \nu_e$
  - Particle misidentification in detector
    - Neutral current resonance:
    $\Delta \to \pi^0 \to \gamma\gamma$ or $\Delta \to n\gamma$, mis-ID as e

Including the new K^+ measurement by SciBooNE in the Feynman Scaling fit reduced the MiniBooNE error on ν_e from K^+ from 32% to 9%.

(32% error included the cross-section uncertainties, normalization problems for few of the data sample used in the Feynman scaling fit prior SB, an extrapolation error from high to lower p_{BEAM})

Conclusion

- SciBooNE experiment measured the K+ production cross section for p + Be -> K^++X at proton beam energy of 8.9 GeV by isolating the high energy events from Kaon decay neutrinos.

- Since this SciBooNE measurement has been made using the same energy booster protons as the BNB neutrino experiments, the measured K^+ production rate can provide an important constraint for the electron neutrino appearance measurements of MiniBooNE and, in the future, MicroBooNE.

- The measurement combined with higher energy data was in good agreement with Feynman scaling and could be used to reduce the uncertainty on the ν_e flux for the BNB experiments.

Conclusions

- SciBooNE experiment K^+ production measurement at the BNB using neutrino and anti-neutrino data (Phys.Rev.D84:012009,2011)

$$\boxed{\frac{d^2\sigma}{dp d\Omega} = (5.34 \pm 0.76)\ mb/(GeV/c \times sr)}$$

- Improved Parameterization of K^+ Production in p-Be Collisions at Low Energy Using Feynman Scaling (Phys.Rev.D84:114021,2011)

- Need to remind that this analysis was done not only by me but also by Gary Cheng (here in the audience) a Columbia University Graduate student.

Thank You!

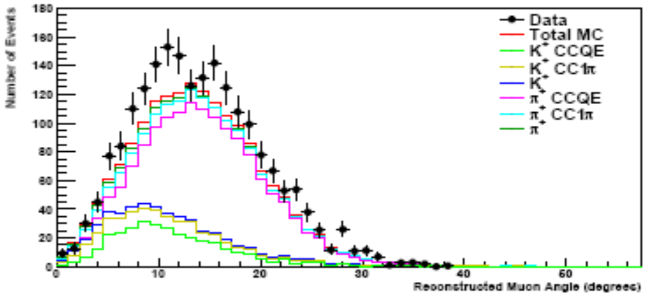
SciBooNE Collaboration

~65 physicists, 5 countries, 18 institutions

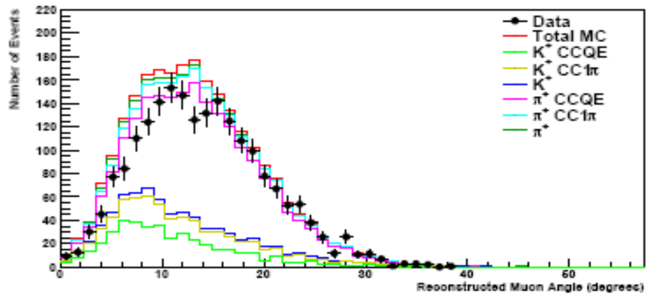
- Universitat Autonoma de Barcelona
- University of Colorado
- Columbia University
- Fermi National Accelerator Laboratory
- High Energy Accelerator Research Organization (KEK)
- Imperial College London
- Indiana University
- Institute for Cosmic Ray Research
- Kyoto University
- Los Alamos National Laboratory
- Louisiana State University
- MIT
- Purdue University Calumet
- Università degli Studi di Roma and INFN-Roma
- Saint Mary's University of Minnesota
- Tokyo Institute of Technology
- Universidad de Valencia

Backup

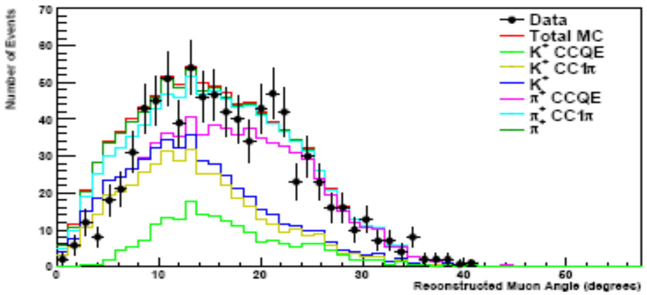
Contributions in ν Mode (B)



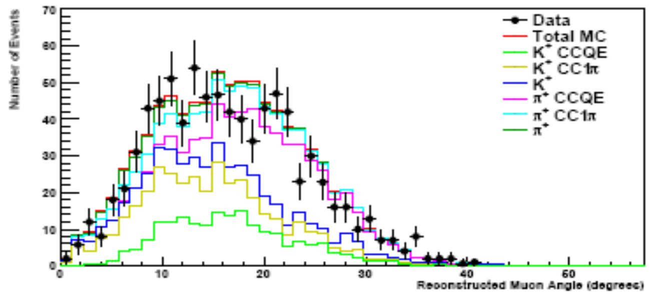
NUANCE 1-track in neutrino mode



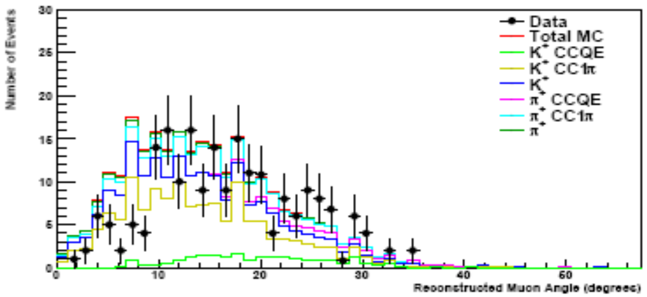
NEUT 1-track in neutrino mode



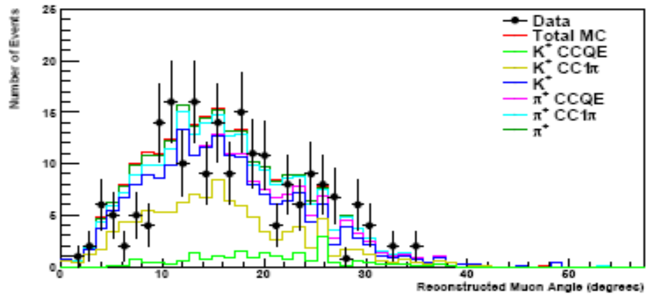
NUANCE 2-track in neutrino mode



NEUT 2-track in neutrino mode

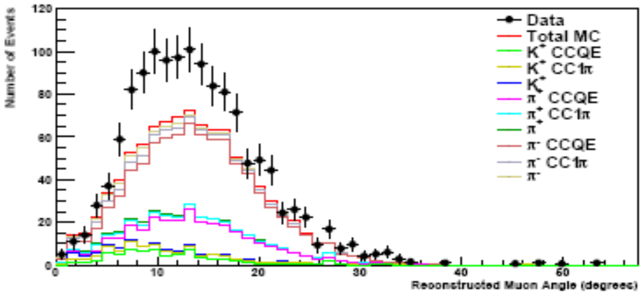


NUANCE 3-track in neutrino mode

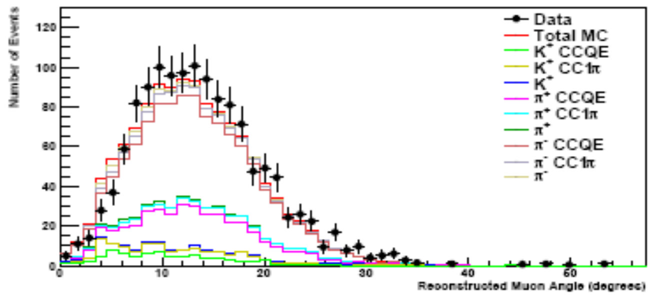


NEUT 3-track in neutrino mode

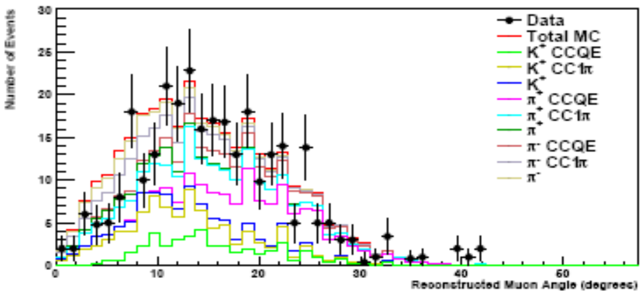
Contributions in $\bar{\nu}$ Mode (B)



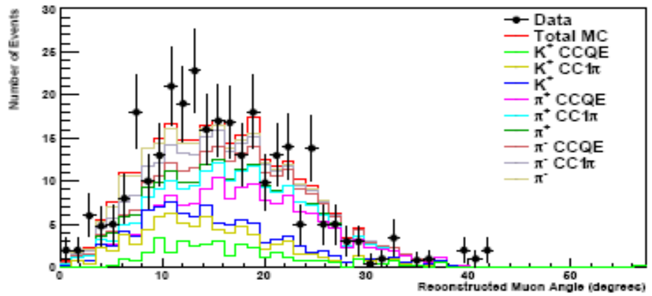
NUANCE 1-track in antineutrino mode



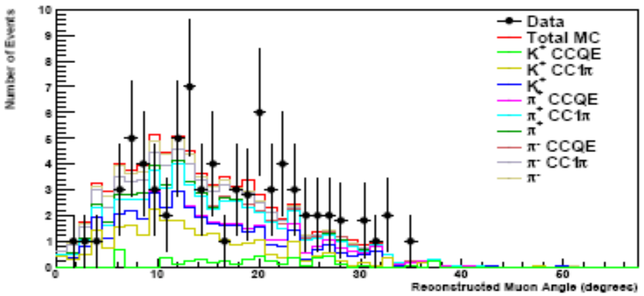
NEUT 1-track in antineutrino mode



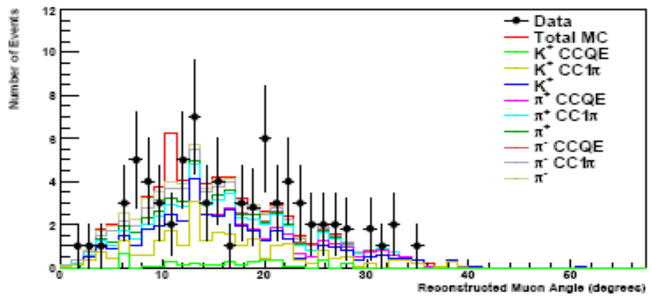
NUANCE 2-track in antineutrino mode



NEUT 2-track in antineutrino mode

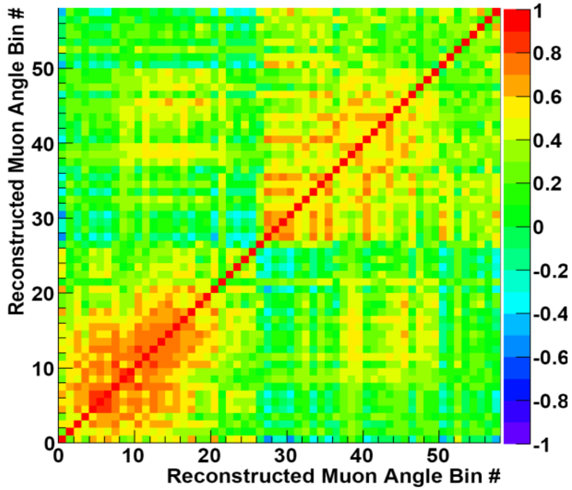


NUANCE 3-track in antineutrino mode



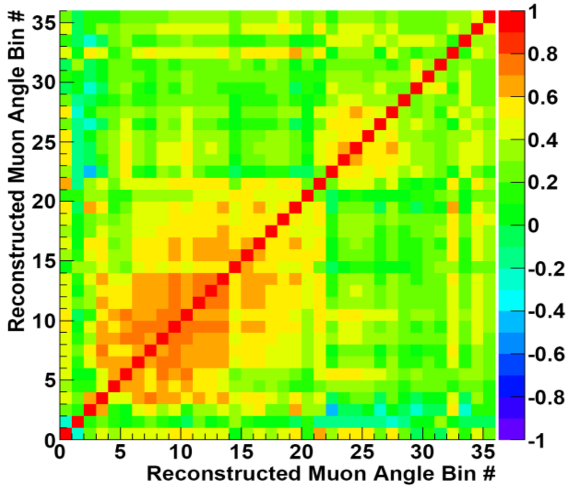
NEUT 3-track in antineutrino mode

Analysis: Correlation Matrices

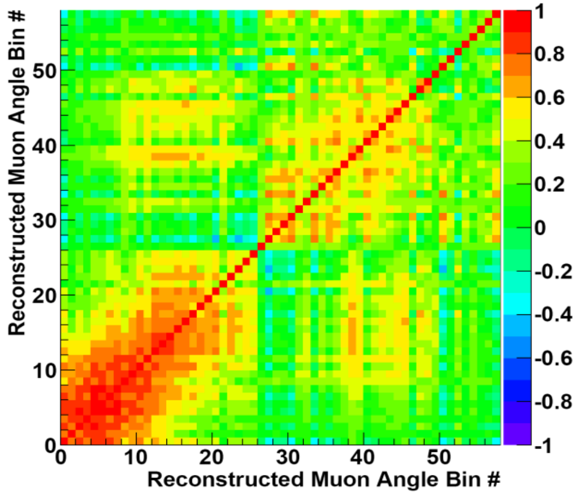


(a) Neutrino Sample

NUANCE

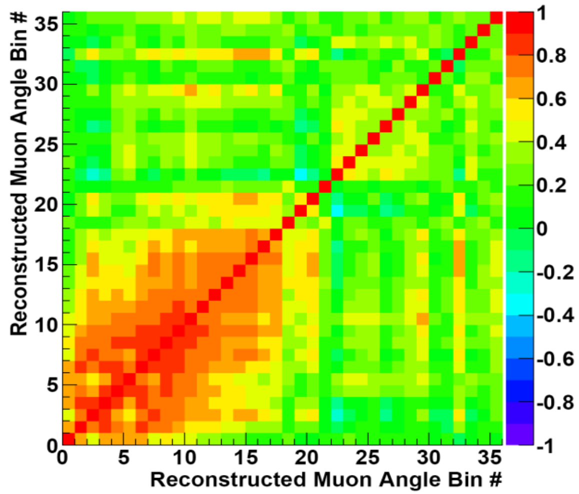


(b) Antineutrino Sample



(a) Neutrino Sample

NEUT



(b) Antineutrino Sample